Climate Change Impacts on Logging Operations and Winter Roads:
Costs and Mitigation Strategies

by

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Abstract

Many cold regions of North America rely on frozen ground for forestry operations to reduce environmental impacts, decrease costs, and access difficult areas surrounded by wet soils. Climate change may influence forestry operations by reducing winter access in those cold regions.

In this thesis, I analyzed the cost of logging operations associated with equipment and labour needs. I developed a cost calculator model to determine the logging costs of a hypothetical mill in Alberta, Canada. I assessed the cost changes under two conditions: first, when wood was hauled to the mill directly; and second, when part of the wood was hauled to satellite yards close to the logging area, thereby minimizing the number of idle hauling trucks. I then used general circulation models (HadGEM2-ES) to predict future winter weather. Logging cost increased over time because more machines and labour will be needed to complete logging in shorter winter. If wood was hauled directly to the mill, the unit cost of logging operations ($\$/m^3$) was projected to increase by an average of 2% to 3% in 2020 – 2039, 3% to 5% in the 2040 – 2059 and 5% to 11% in the 2070 – 2089 compared to the base year. With use of satellite yards, the total logging cost was estimated to increase by 2% to 3% in the 2020 – 2039, 3% to 6% in the 2040 – 2059 and 5% to 11% in the 2070 – 2089 periods. The results suggest that in the event of an extremely warm winter, equipment needs would be more than double at the end of the century.

Then, I analyzed the cost of roading if logging operations were shifted from winter to the summer season. I calculated the costs of temporary roads (both winter and summer) for four harvesting units with different levels of difficulty of access; variables included the length of the road network, stream crossing, and the amount of corduroy road for wetland crossing. Then, I

analyzed the changes in roading cost for summer access under different soil wetness that affects the amount of corduroy. The longer road networks and the building of corduroy roads were the costlier additions to summer roading costs. The average cost of temporary road construction increased from 1,200 \$/km or 0.30 $\$/m^3$ in winter to 5,900 \$/km or 2.14 $\$/m^3$ in summer. The roading costs in summer (\$/km) were expected to be 2 to 6.7 times more than winter road cost. This study showed that when logging switched from frozen to non-frozen, the average cost of roading will increase depending on soil wetness, amount of corduroy requirement, and wood basket in the area.

Finally, I developed temperature prediction models to predict roadbed frost penetration in fall and decay in spring. This was used to estimate the length of winter weight premium (WWP) that allows logging trucks to carry heavier loads on the highway. General circulation model outputs were then used to predict future length of the WWP and I calculated the cost of trucking based upon shortened WWP season. WWP period was projected to decrease by up to 5 days in 2020 – 2039, 13 days for 2040 – 2059 and 32 days for 2070 – 2089. The trucking costs due to shorter WWP period during the extremely warm winter was predicted to increase by up to 2% in 2020 – 2039, up to 6% in 2040 – 2059 and up to 8% in 2070 – 2089 when wood hauled directly to the mill. With the satellite yard use, the trucking costs will increase by up to 5% in 2020 – 2039, up to 8% in 2040 – 2059 and up to 16% in 2070 – 2089. This study showed that the length of WWP decreased, resulting in increased trucks during winter when wood hauled directly to the mill. With the use of satellite yards, fewer hauling trucks were needed but costs were higher because of the additional unloading and re-loading at satellite yards and smaller loads in summer.

Future studies might focus on: 1) exploring the landscape level analysis and timber supply models; 2) examining corduroy alternatives, such as rig mats, timber bridges and brush mats 3) heuristic modelling to allocate adaption options to warming climate and sensitivity analysis of logging costs that impacted by uncertain climate variables.

Preface

This thesis is an original work by Tevfik Ziya Kuloglu. I was responsible for all data analysis and writing. Victor J. Lieffers and Axel E. Anderson were involved with concept design and manuscript writing, reviewing and editing.

Chapter 2 of this thesis has been published as T. Z. Kuloglu, V. J. Lieffers, A. E. Anderson, "*Impact of Shortened Winter Road Access on Costs of Forest Operations"* in Forests, (10)5, 447, 2019. The study was conceived and designed by myself, V.J.L. and A.E.A. I conducted the analysis and creation of spreadsheet model. I wrote the first draft of the chapter and V.J.L and A.E.A. contributed to editing and reviewing manuscript.

Chapter 3 is being prepared for submission as a journal article, entitled "*Cost comparison of summer and winter forest road construction in uncertain climates*". The study was conceived and designed by myself, V.J.L. and A.E.A. I located road network layout and conducted the data and cost analysis. I wrote the first draft of the chapter and V.J.L and A.E.A. contributed to editing, reviewing and writing manuscript.

Chapter 4 is currently prepared for submission as a journal article, entitled "*Duration of frozen highway conditions and highway hauling costs in future climate scenarios*". The contributors are Kuloglu, T. Z., Lieffers, V. J., Anderson, A. E., Fitzios, A., This study was conceived and designed by myself, V.J.L. and A.E.A. The data gathered by A.F. I developed and validated the roadbed temperature prediction models. Hauling cost used in this chapter is the modified version of chapter 2. I wrote the first draft of the chapter and V.J.L and A.E.A. contributed to editing, reviewing and writing manuscript.

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Chapter 1: Introduction

1.1. Winter Forest Operations

Many cold regions rely on winter forest operations to reduce environmental impacts, decrease costs and access difficult areas surrounded by wet soils. Frozen snowpack and soil provide stable forest operations.

Reduced Environmental Impact

Machine traffic during forest harvesting can affect soil, water, habitats, aesthetics and economics efficiency (Alberta Agriculture and Forestry, n.d.). Winter harvesting in times of ground frost can protect the forest floor layer of wet soils, keeping the soil profiles intact; this favors natural regenerations and reduces the need for supplemental planting of trees (Frey et al., 2003). Frozen soil conditions also avoid soil degradation from rutting or soil compaction from heavy machines (Barrow et al., 2004; Rittenhouse & Rissman, 2015). Snow cover reduces damage to vulnerable understory plant species and protects feeding areas for animals during the winter harvest. Bird nesting activities during the summer and spring season can be avoided when forest operations occur in winter.

Decrease Costs

Costs in the Woods:

Road construction, decompaction, and planting of roads / harvesting sites affect logging cost differences between winter and summer. These costs can be reduced during winter operations. In contrast, summer road building needs more clearing and piling, excavation and soil compaction of the road surface. These roads then need decompaction and rollback of organic layers onto the former road surface. Temporary roads in order to access harvesting sites cost less to build in winter because ice roads can be constructed to cross wetlands simply by icing and smoothing a frozen surface. Temporary roads built on the soil with frozen water particles also requires less reclamation and decompaction and artificial regeneration because the frozen ground protects the soil and propagules from damage.

Winter Weight Premium:

Permanent roads, highways, provide all year use, with some restrictions on vehicle weight depending on the seasons to minimize the maintenance costs and road damage such as rutting, cracking, frost heave raise and road deflection. The increased gross vehicle weight (GVW) during the winter season does not damage highways because the ice matrix in the subgrade increases the road bearing capacity by creating a strong bond between particles and increasing the stiffness of the soil (Johnson et al., 1986; Bigl & Berg, 1996; Asefzadeh et al., 2017; Lachance-Tremblay et al., 2017; Bilodeau et al., 2019). Gross vehicle weight in winter can increase up to 40% higher weight in summer. The increased truck carrying capacity in winter (called Winter Weight Premium (WWP) or Winter Weight Allowance) results in significant savings in the transportation costs for forest companies. Trucks can carry heavier loads with fewer trips from the harvest areas to the mill site that will decrease the truck traffic on the highway roads.

Access difficult areas surrounded by wet soils:

Winter and summer roads have different construction techniques and are laid out using different strategies to minimize costs and environmental impact in the different seasons. In winter, temporary roads can be located on flooded wetlands in order to provide winter crossing. Snow and/or ice bridges can be used to cross intermittent streams. However, wetlands with flowing subsurface water or part of a flowing water system and seasonally fluctuated wetlands are avoided because such substrates are difficult to cross with winter roads (British Columbia Ministry of Forest, 2002, Ducks Unlimited Canada et al., 2014, Partington et al., 2016). Also, forestry companies can take advantage of seismic lines that were built by oil and gas companies in order to avoid clearing costs of temporary roads. Water sprayed to compacted snow increases the surface strength of temporary roads (Abele, 1990; Partington et al., 2016).

1.2. Climate Change Impact on Winter Logging

The historical climate data (Alberta Agriculture and Forestry, 2019; Kienzle, n.d.) and future predictions (Johnston et al., 2008; Price et al., 2011; Thornton et al., 2012; Vincent et al., 2012; Wang et al., 2016,) show warming trends. Increases in mean winter temperatures will be greater than summer temperature changes. The mean winter temperature, between December 1 and March 31, in Alberta, increased by 5 °C between 1950 and 2010 (Kienzle, n.d.). Increased winter temperature decreases the period of frozen soil conditions resulting in reduced access for harvesting sites and the eligible days for logging operations. For example, winter operations start time was delayed until January in Saskatchewan in 2005 – 2006 or in Alberta in 2016 (Johnston et al., 2010). Moreover, frequent and longer mid-winter thaws will breakdown the temporary snow and ice roads. Rebuilding temporary winter roads will add extra cost to the road building budget. The warmer winter season will also impact the wetland crossing. Heavy equipment on the unstable frozen ground might damage sensitive wetland soil. Moreover, forestry companies might decide to harvest in summer to avoid unreliable ice roads on wetlands. Accessing winter sites, however, in summer will increase the cost of road construction. In addition, the continued warming trend will affect the length of WWP. The GVW will be restricted during the breakup and thawed seasons because highways are particularly vulnerable and easy to damage due to excess soil water caused by the melted ice. Thus, the profitability of forest companies is impacted by the weather patterns in fall, winter and spring, and it is vulnerable to the warming climate. The reduced days of frozen ground causes workday loss and reduced harvesting rate might lead to an increase in delivered wood costs and a financial struggle for the forestry sector (Spittlehouse, 2005, Geisler et al., 2016).

HadGEM2-ES is an Earth System Model with three Representative Concentration Pathways (RCPs) that was used in this study. Earth system models combine the interactions of atmosphere, ocean, ice, and biosphere to project climate (Heavens et al., 2013). We analyzed future predictions with three greenhouse gas radiative forcing values of 2.6, 4.5 and 8.5 using HadGEM2-ES for three time interval 2020 – 2039, 2040 – 2059 and 2070 – 2089.

1.3. Adaptation Strategies to Shorter Winter Season

It is predicted that in some winters, planned logging and hauling operations across wetland sites may not be completed in the winter period. To address the uncertainty associated with changing the length of winter logging season and mid-winter thaws, managers are employing several strategies. These include providing more machines and labour, using satellite yards (Alberta Agriculture and Forestry, 2016), contingency planning for timber that is accessible in summer (Williamson et al., 2009), increased investment in permanent (all-weather) roads (Lemmen et al., 2008), and using night hauling and operations when the overnight temperatures refreeze soils (Kestler, 2000). These strategies do help manage the changing winter conditions, however, they come with costs. Increasing number of equipment in order to finish winter logging operations in a shorter time, results in idle equipment and operators during the summer time; this makes it difficult to maintain a skilled workforce because workers take other jobs that can provide consistent employment. Satellite yards are temporary log storage areas in close proximity to logging sites (Chan et al., 2009). Satellite yards offer flexibility for operations managers to increase the hauling truck cycles per day out of the winter blocks compared to relatively few loads moved per day if the haul is directly to the mill yard. In this case, companies transport wood to satellite yards when there is a risk of winter roads break-up. In summer, wood is then re-loaded and hauled to the mill on permanent roads. Satellite yards can also supply wood to the mill in summer when the weather or bird nesting season curtails activities in the forest. By doing this, forestry firms can also decrease idle hauling truck costs and provide nearly year-around employment opportunities for the trucking fleet. Another strategy is to access winter harvesting sites in summer. Rittenhouse & Rissman (2015) showed that decreasing frozen ground condition changed harvesting operations by shifting harvest to dry and well-drained soils and decreasing harvest on poorly drained soils. Accessing winter harvest sites during the summer requires expensive temporary summer roads with a subgrade such as corduroys constructed of a bed of logs. Using corduroy roads, brush mats or rig mats provide a bridging effect to distribute forces from the load (both road fill and machine traffic) to minimize damage to soil and wet areas (Sessions, 2007). The extent of use of such roads and their reliability in summer is also dependent on rainfall patterns.

1.4. Winter Logging in Alberta Context

The Boreal Plains in Alberta (Figure 1.1) consists of areas of upland forested land surrounded by peatlands (Natural Resources Canada, 2018) and streams. The Boreal Plain region covers 381,711 km^2 and supplies 47 of the 50 mills in Alberta, and accounts for 28.2 million m^3/year, which is for more than 90% of Alberta's annual harvest (Environment and Sustainable Resource Development, 2017; Alberta Wood Products, 2019). Bogs, fens, marshes, and shallow water cover 40% of boreal plains ecozone (Vitt et al., 1996; Natural Regions Committee, 2006). A large portion of the timber in the boreal forest of northern Alberta and cooler regions of North

America do not have road access and can be accessed only by temporary ice roads in winter when substrates are frozen. Forestry operations on these wet landscape rely on frozen ground condition to harvesting sites, to operate within sites and transport equipment and hauling of wood (Rittenhouse & Rissman, 2015). Winter roads are especially important for regions such as Alberta's boreal forest region where there are high amounts of wetland and fine-textured soils that are prone to rutting. Winter logging operations are relatively cheap compared to summer operations. Hauling cost is the highest part of logging costs (Spittlehouse, 2005; Pan et al., 2008; Kuloglu et al., 2019). Jurisdictions (province, state, municipality, etc.) usually increase the gross vehicle weight (GVW) on public highways during winter frozen conditions. Greater loading capacity will decrease the number of trip required to haul wood and results in less expensive hauling costs.

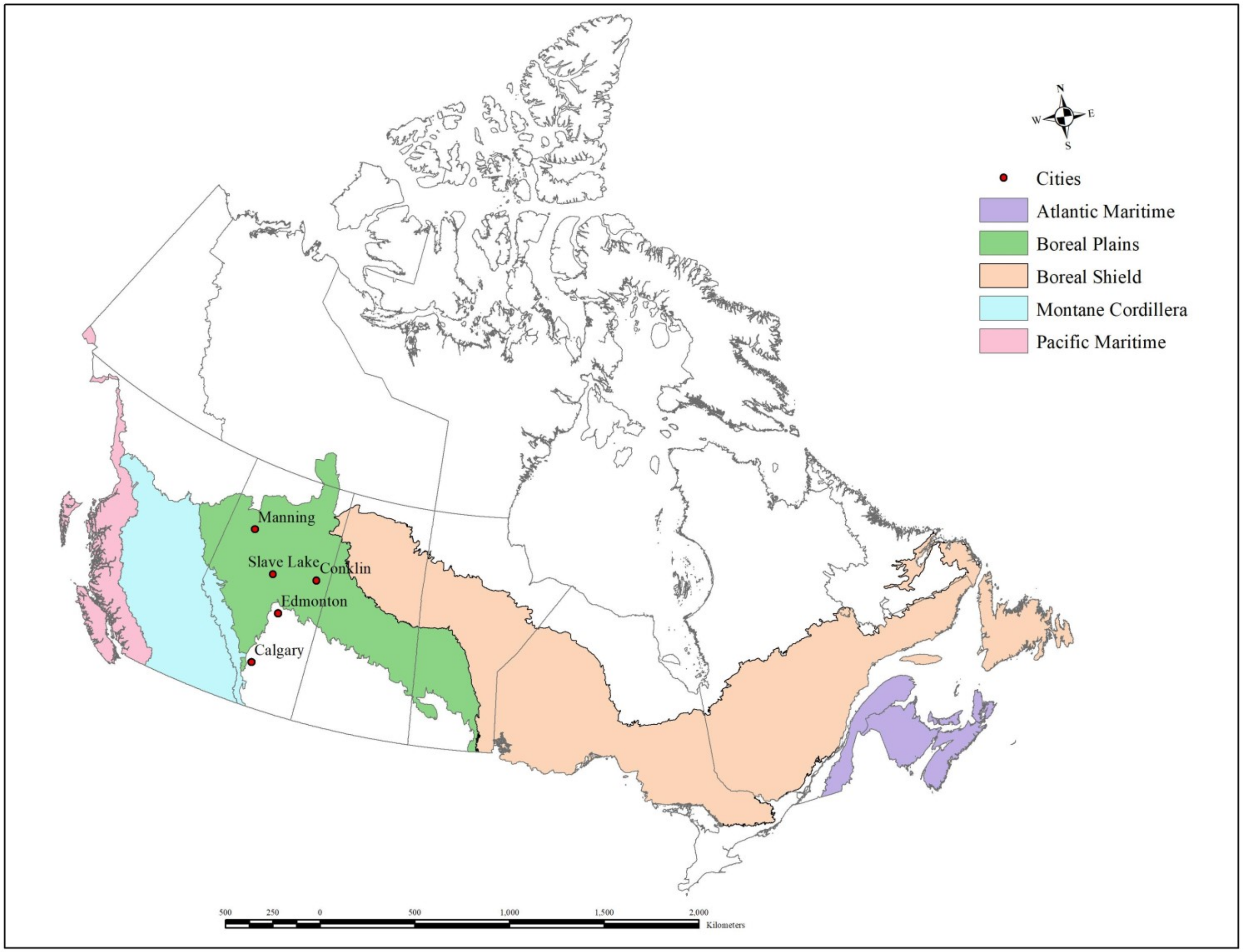

Figure 1.1 Main natural subregions in Canada with major cities and study area in Alberta (Natural Resources Canada)

1.5. Thesis Structure and Objectives

This thesis analyses the cost impacts of climate change on different components of winter forest operations in Alberta, and also presents some associated strategies that can be employed to cope with shorter winter. It contains three research chapters that address: 1) the costs associated with equipment and labour needed for forest harvesting; 2) the road cost associated with switching winter harvest areas to the summer harvest; and 3) the hauling cost impacts of shorter Winter Weight Premium (WWP) programs.

In chapter 1, general information about winter forest operations, climate change effect on winter logging and possible adaption options were provided.

The objective of chapter 2 was to use general circulation model (GCM) outputs to assess the future equipment and labour costs for logging. We determined the equipment needs to cut, process and haul wood to supply a hypothetical pulp mill operation in Alberta, Canada. The analysis included the total costs estimate of logging operations but with different periods of time available for suitable winter operating conditions. The time available for winter logging was determined at three time intervals (2020–2039, 2040–2059, and 2070–2089). Finally, we assessed the equipment needs and costs to the forestry company to prepare for the warmest winter in each of these three-time intervals. We also assessed a scenario when all of the wood was hauled directly to the mill and secondly, a scenario when some portion of the winter harvest volume was hauled to satellite storage yards and the mill yard. If there are fewer frozen days, more equipment and labour will be needed. Much of this extra equipment, however, will be idle during the summer, but ownership costs will add to the total logging cost.

The objectives of chapter 3 were: 1) to calculate the costs of winter road construction for operational harvesting units with different landscape conditions, especially the level of and distribution of wet soil types; 2) to calculate the cost of summer road construction of these same winter harvesting units - variables include the length of the temporary road network, stream crossings and the amount of the corduroy road needed for wetland crossing; and 3) to analyze the road construction cost changes for both winter and summer access under the base case soil wetness, as well as with possible different wet and dry scenarios.

When harvesting operations switch from winter to summer, corduroy roads were necessary to increase the road bearing capacity and to cross wet sites. The amount of the corduroy was based on soil wetness and drainage pattern that increased or decreased the cost of road construction.

In chapter 4, we developed regression models to predicted frost depth and used General Circulation Models (GMCs) to examine future change on the length of WWP period. Increasing warming winter trends resulting in declined WWP days will economically impact forestry and trucking industry by purchasing more hauling trucks or using satellite yards. The objectives of chapter 4 were: 1) to predict future periods of winter weight premium (start and end days) for three location in Alberta; and 2) to assess Alberta future hauling cost on the highway in relation to the length of future WWP period in Alberta under the two scenarios. First, when all the wood was hauled directly to the mill and second when a portion of the winter harvest volume is hauled to a satellite yard and then the mill yard in summer. The temperature prediction models predict frost depth and the number of days of WWP based upon four years of environmental data. The road bed temperature models used the minimum, maximum and average air temperature, freezing degree days and thawing degree days as independent variables.

In chapter 5, major findings of this thesis and adaption options were explained.

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Chapter 2: Impact of shortened winter road access on costs of forest operations

2.1. Abstract

A significant portion of the forest harvesting in the cooler regions of North America occurs in the winter when the ground is frozen and can support machine traffic. Climate change may influence the cost of forestry operations by reducing the period of winter access in those cold regions. In this study, we examined the impact of a shortened period of frozen ground conditions on logging operation and costs. To adapt to shorter period of frozen soil conditions, logging contractors might need to provide more machines and labour to complete logging in a shorter period of frozen conditions. The objectives were to calculate the costs of logging operations of a hypothetical forestry company in Alberta, Canada under two conditions: first, when the wood was hauled to the mill directly; and second, when part of the wood was hauled to satellite yards close to the logging area, thereby minimizing the annual number of idle hauling trucks. General Circulation Models (GCM) were used to predict future winter weather conditions. Using the current type of harvesting machines and hauling directly to the mill, the unit cost of logging operations ($/m^3) was projected to increase by an average of 2% to 3% in 2020 – 2039 period, 3% to 5% in the 2040 – 2059 and 5% to 11% in the 2070 – 2089 compared to the base year of 2015–2016. With use of satellite yards during the winter logging, the total logging cost will increase over direct haul, by 2% to 3% in the 2020 – 2039, 3% to 6% in the 2040 – 2059 and 5% to 11% in the 2070 – 2089. Using satellite yards, however, will provide year-around employment for hauling truckers and more consistent and reliable hauling operations.

2.2. Introduction

The boreal region in Canada consists of areas of upland forested land interspersed with peatlands (Natural Resources Canada, 2005), lakes and streams. A substantial portion of the timber in the boreal forest is without road access and can be accessed only by temporary ice roads in winter when substrates are frozen. Frost on this wet landscape can provide a firm substrate for logging equipment and hauling (transporting) of wood (MacDonald, 1999). The frozen conditions reduce logging costs compared to summer operations. The construction, decompaction, and planting of the roads are the factors affecting logging cost changes between seasons. Moreover, the winter weight program (Alberta Transportation, 2015) in Alberta is a large component of the cost difference. As logging costs are the biggest costs to forestry firms, the impact of shortening the length of the frozen period (Spittlehouse, 2005) will be a financial challenge to forestry companies (Geisler et al., 2016) in this boreal region. In severe warming conditions there may be significant access constraints that have the potential to hinder wood supply and jeopardize the economic sustainability of forest companies.

Machine traffic during forest harvesting can affect soil, water, habitats, aesthetics, and economic efficiency (Alberta Agriculture and Forestry, n.d.). Winter harvesting in times of ground frost can protect the forest floor layer of wet soils, keeping the soil profiles intact; this allows sprouting regrowth of poplar trees (mostly *Populus tremuloides Michx*.) the following spring (Frey et al., 2003). Frozen soil conditions also avoid soil degradation from rutting or soil compaction from heavy machines (Aust & Blinn, 2004). Even roads within cutblocks areas can be produced simply by the recrystallization of packed snow into a smoothed ice surface for hauling trucks with minimal damage to the forest floor beneath. In contrast, summer road building needs more clearing and piling, excavation and compaction of the road surface. These roads then need decompaction and rollback of organic layers onto the former road surface. This makes summer access less desirable than winter access and more likely to produce failed natural regeneration (Frey et al., 2003) and the need for supplemental planting of trees.

The historical climate data, as well as future predictions for the western boreal forest of North America, show warming trends. It is expected that the mean annual temperatures will increase but the temperature increase in winter will be greater than for summer. The mean winter temperature, between December 1 and March 31. In Alberta, the temperature increased 5 °C between 1950 and 2010 (Kienzle, n.d.). The mean winter temperature in this area is predicted to increase a further 1 °C to 3 °C by 2020 – 2039, 2 °C to 5 °C by the 2040 – 2059 and 3 °C to 8 °C by 2070 – 2089 (LarsWG (Semenov & Barrow, 2002), Daymet (Thornton et al., 2012), climateNA (Wang et al., 2016)).

Temporary winter road construction starts at the beginning of the winter; harvest operations, including hauling/transporting and clean-up, must be completed before the soil thaws in spring (known as the break-up season) (British Columbia Ministry of Forestry, 1995). Rittenhouse & Rissman (2015) showed that decreasing frozen ground conditions changed harvesting operations by shifting the harvest to dry and sandy soils and decreasing the harvest on poorly drained soils. Furthermore, start-up of winter harvest operations were delayed if the on-set of winter was delayed (Barrow et al., 2004): e.g., in Saskatchewan, in 2005 – 2006, winter operations did not start until January (Johnston et al., 2010), and in Alberta, in 2016, there was a mid-December onset of operations. In addition, longer thaws during the winter risk breakdown of snow/ice roads in winter adding to rebuilding costs or potential abandonment of the remainder of the winter logging season. To address the uncertainty associated with changing the length of the winter logging season and mid-winter thaws, managers are employing several strategies. These include providing more machines and labour, using satellite yards (Alberta Agriculture and Forestry, 2016), increased investment in permanent (all weather) roads (Lemmen, 2008), more planning and harvesting summer accessible areas (Williamson et al., 2009), and operating at night when the overnight temperatures help maintain frozen soils (Kestler et al., 2000).

Wood is generally stockpiled in a yard at the mill site and used in the mill throughout the year. In contrast, satellite yards are temporary log storage areas in close proximity to logging sites (Chan et al., 2009). Satellite yards offer flexibility for operations managers to increase the hauling truck cycles per day from the winter blocks compared to the relatively few loads moved per day if the haul is directly to the mill yard. Furthermore, hauling truckers can only work a certain amount of time in a day and often cannot run multiple loads to the mill because the mill is far away from the logging sites. In this case, companies may have to transport most of the wood to satellite yards. In years when winter roads break-up because of the temperature increases, managers may use satellite yards exclusively to empty the logging sites, and store the wood until it can be hauled to the mill in summer.

Satellite yards can also supply wood to the mill in summer when the weather or bird nesting season curtails activities in the forest. By doing this, forestry companies can also decrease idle hauling truck cost and provide nearly year-around employment opportunities for the trucking fleet. Satellite yards, however, come with additional costs of unloading, reloading the wood, the cost of the mobile weight scales, and the fact that less wood can be loaded onto hauling trucks to meet summer weight restrictions on publicly owned highways.

It is predicted that in some winters, planned logging and hauling operations across wetland sites may not be completed in the winter period unless there is an increase in the machine and human resources devoted to the harvesting and hauling in a limited time.

The objective of this study was to assess the future logging costs in relation to the equipment and labour needs if warming trends increase to those projected by general circulation models. If there are fewer frozen days, more equipment and labour will be needed. Much of this extra equipment, however, will be idle during the summertime, but ownership costs will add to the total logging cost. In this paper, we determined the equipment needs to cut, process and haul wood to supply a hypothetical pulp mill operation in Alberta, Canada. The analysis includes the total costs estimate of logging operations but with different periods of time available for suitable winter operating conditions. The time available for winter logging was determined for three time intervals (2020 – 2039, 2040 – 2059, and 2070 – 2089). Finally, we assessed the equipment needs and costs to the forestry company to prepare for the warmest winter in each of these three time intervals. We also assessed a scenario when all of the wood was hauled directly to the mill and secondly, a scenario when some portion of the winter harvest volume was hauled to satellite storage yards and the mill yard.

2.3. Materials and Methods

2.3.1. Study Area

The mill was located in Alberta and the company harvested mostly broadleaf trees. Thus, we collected weather data from an undisclosed location in Alberta at a mid-point of this hypothetical forest and future predictions of the weather were modelled for this location. The weather prediction was modelled for a specific location in northern Alberta but the exact location is not disclosed to prevent erroneous linkage of this study with a specific firm. On a typical year, the forestry company was assumed to harvest 750,000 m^3 in the summer season and 1,500,000 m^3 in the winter season. Reduced logging costs are one reason for winter logging; however, some sites are very isolated and cannot be accessed in summer, while other sites have poorly drained soils and will sustain too much soil damage if trees are felled and skidded on unfrozen ground, so permits cannot always be obtained to harvest and haul in summer.

2.3.2. Defining the Winter Season and Shut-Downs

We use the term logging operations to describe the combined activities of supplying wood to the mill. For this paper, logging operations components were defined as:

1. Harvesting, which include felling, skidding, and delimbing.
2. Loading, which included loading and unloading of hauling trucks in harvest blocks and satellite yards.
3. Hauling as the trucking of wood to the mill or satellite yards.
4. Preparation and cleaning which included building access road (excavating), decompaction of access roads and planting/seedling of access roads.

The winter logging season starts November 1st and continues until March 31st. The freeze-up period for winter roads building occurs in November, and harvesting and hauling starts on December 1st based on the temperature. We set the threshold for determining a shut-down day for hauling operations to a day when maximum air temperature reached 6 °C. For expediency, we selected this simple threshold because in general the thaw during the daytime would be offset by refreezing during night. Also, the large thermal mass of the soil would take time to thaw at moderate temperatures above freezing. Hauling operators (personal communication) noted that hauling continued until a 6 °C threshold is reached. We made a simple adjustment for shut-down of felling, skidding, delimbing, and excavating operations within the cutblocks. As a loose snow cover insulates the ground surface within blocks and delays melting, we estimated that there were one quarter fewer shut-downs for these activities within the block than we assumed for hauling. Sundays and holidays were also removed from operation days.

2.3.3. Historical Weather Data

We used the ACIS (Alberta Agriculture and Forestry, 2019) and the Daymet (Thornton et al., 2012) dataset to obtain the mean daily and range of daily temperature for 1960 to 1980 and for 1995 to 2015 (Figure 2.1). Determining the temperature when the frozen ground starts to melt is complicated by various factors, such as temperature, solar radiation, cloud cover, solar angle, and shade from the forest edge.

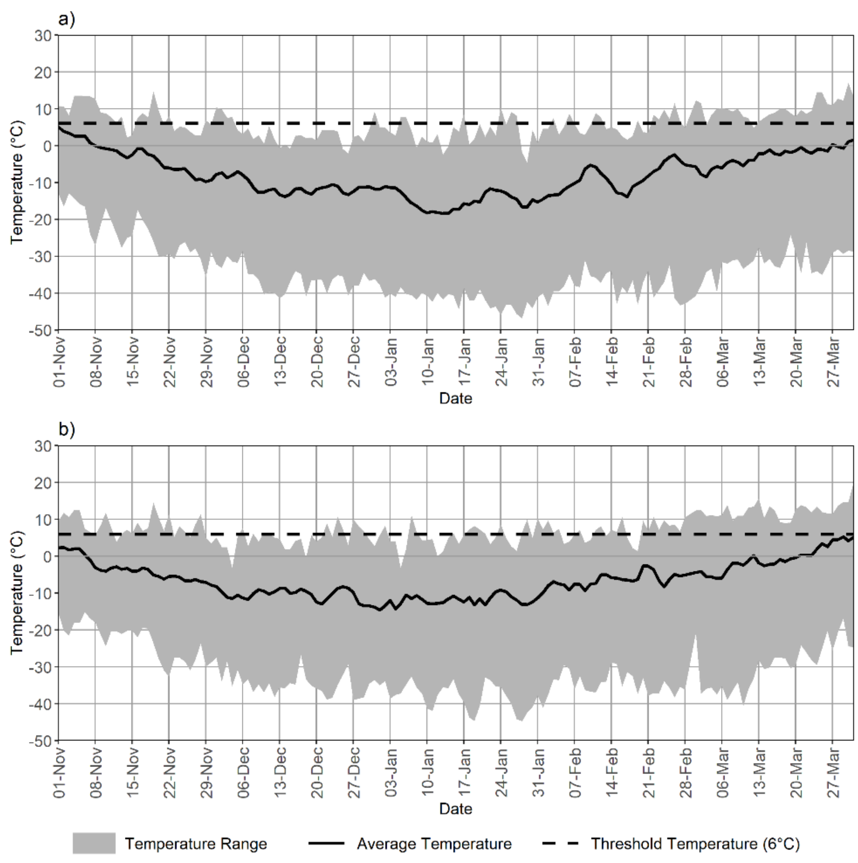

Figure 2.1 Range and average daily temperature for the period between a) 1960 and 1980, and b) 1995 and 2015. The upper range is the extreme high and the lower range is the extreme low temperatures for each day of this 20-year period. Note, however, that every extreme high point above 6 °C is a shut-down day, but these did not all occur during the same year.

2.3.4. Future Climate

We chose three Representative Concentration Pathways (RCPs) (Rogelj et al., 2012), with greenhouse gas radiative forcing values of 2.6, 4.5, and 8.5, for future predictions. Under the RCP 2.6 emission scenario, radiative forcing reached the peak point in the mid-century and will decrease by 2100 (Van Vuuren et al., 2011b). The RCP 4.5 assumes that population growth will decrease at the end of the century, while the global economy will have a consistent increase and a consistent land use/cover distribution will be established (Thomson et al., 2011). On the other hand, the RCP 8.5 assumes that urban demands for energy will increase with the population now associated with relatively low economic development, and there is less concern about environmental preservation (Van Vuuren et al., 2011a).

The climate model HadGEM2-ES was selected from the climate models available (EC-EARTH, GFDL-CM3, HadGEM2-ES, MIROC5, MPI-ESM-MR) because this model covers all of the scenarios that we planned, while other models do not include an RCP 2.6 scenario. Moreover, Sheffield et al. (2013a, 2013b) showed that—HadGEM2-ES received a higher pattern correlation coefficient, and lower bias and errors than the other models.

We used the Lars-WG (Semenov & Barrow, 2002) stochastic downscaling weather generator model (based on Markovia Chain (Racsko et al., 1991)) that produces daily maximum and minimum temperatures projections for the 2020 – 2039, 2040–2059 and 2070 – 2089; these are climate projections from the fifth phase of the Coupled Model Intercomparison Project (CMIP5).

2.3.5. Cost Calculator

A spreadsheet model (Appendix A.1 – Appendix A.10) was created to calculate the cost of logging operations based upon the productivity of the equipment and the number of machines needed to complete harvesting/hauling during the winter days with frozen conditions vs.

harvesting/hauling in the summer season. The model created for this study was adapted and advanced from the Auburn harvesting analyzer (Tufts et al., 1985). The Auburn harvesting analyzer calculates unit prices of only felling, skidding, delimbing, loading, and hauling. We included preparation (road building-excavating) and clean-up processes (decompaction and planting/seedling) in our spreadsheet model to calculate costs for the entire forest management area and future weather conditions. We also added the time of the idle equipment, costs of both active and idle time, and the logging costs with different periods of winter thaw.

The unit cost ($\$/m^3$) for the equipment of each phase of a logging operation consisted of ownership costs, labour costs, and operational costs (Brandstrom, 1993), as well as road decompaction costs ($/km), road clearing/piling cost–road building costs ($/km), and road planting/seedling costs ($/ha). The total costs of decompaction, clearing/piling, and planting/seedling were calculated and converted to the $\$/m^3$ by dividing total cost to the seasonal harvest volume. We assumed that the proportion of wood accessed in winter and summer was unchanged over time, despite the fact that winters with frozen conditions may be shorter.

The ownership cost was the total of depreciation, return on capital, and insurance. The wage information to calculate the labour cost was gathered from the Government of Alberta Occupations Info website (Alberta Alis, n.d.). The operational cost included fuel, oil and lubrication, repair, and maintenance costs. The total cost of logging in winter and summer (separately) was the sum of harvesting, hauling, loading-unloading, road building, road decompaction costs (only for summer season), and the planting cost of roads (only for the summer season) and idle equipment costs. Only the average direct cost of access roads building was considered in this study. Stumps needed to be removed (clearing) for the summer season, but stumps could be sheared with a bulldozer and the snow packed to more easily create a winter road; thus, only the piling cost was included in the calculator for the winter season. Furthermore, the decompaction cost was only calculated for the summer season because frost and snow cover should protect soil from damage. It was assumed in this study that additional planting/seedlings were not needed for the winter season; however, because of the compacted soil, both decompaction and planting/seedlings were required for summer logging. Decompaction and regeneration were only considered on access roads, not in the cutblocks. We assumed that when private contractors prepare contract bids, they implicitly account for overtime wages, bank interest, equipment transportation, and other costs.

Winter logging operations were assumed to continue almost 24 h per day (Ontario Centre for Climate Impacts and Adaptation Resources, 2011) on work days. The work hours of the summer season were considered as 21 h and 19 h for the winter season. It was assumed that there would be a three hour loss for summer and a two hour additional loss in winter because of the maintenance time of the machines, shift changes, warming up of the equipment and the occasional storm conditions that were removed from work hours. It is assumed workers take their day off during the shut-down days. Employees may work up to 12 h (Government of Alberta, 2018), and a driver should not exceed 13 h of driving time (Government of Alberta, 2017).

The model consists of input sections where cost was adjusted in relation to inputs and a summary panel (Appendix A.1). The summary panel of the calculator was used to enter harvest volume, work hours per day, operation days, as well as shut-down days and access road length. With these inputs, results were represented in the same panel. The model calculates each step of the logging operations: Felling (Appendix A.2), Skidding (Appendix A.3), Delimbing (Appendix A.4), Loading (Appendix A.5), Hauling (Appendix A.6 and Appendix A.7), and Road Building

(Excavating) (Appendix A.8), as well as decompaction (Sessions & Sessions, 1992), and planting/seedlings on access roads (USDA, 2017). The annual unit cost ($\$/m^3$) in this study was the sum of each operation cost divided into total annual harvest volume. Kuhnke et al. (2002) surveyed the logging cost in Alberta between 1997 and 1998 from 29 forest companies and our values from the calculator were in the range that they reported.

To understand the impact of shorter winters on future predictions, hauling volume and the length of access roads are assumed to be the same as the 2015–2016 data. Technological development for the machines, such as their productivity, machine power, ability to work on soft soil, and fuel consumption were held constant into the future.

2.3.6. Hauling to the Mill Only

2.3.6.1. Input Data

It was assumed that the average haul distance of a loaded hauling truck was 250 km with 8 h per cycle. The average speed of loaded hauling truck is 55 km per hour and 85 km per (Dratchev, 2013) hour for the unloaded truck. We assumed 600 km of access roads were built each year in winter and 300 km in summer. The difference in winter and summer road length was because twice as much volume was harvested in the winter in comparison to the summer.

The logging cost for each machine was divided into three parts: ownership cost, labour cost, and operation cost.

2.3.6.2. Model Formulation

Ownership costs, also known as fixed costs, are not affected if the equipment is being operated or sitting idle. The ownership costs were calculated annually, commonly in dollars per scheduled machine hour (Bushman & Olsen, 1998). The ownership costs (Fc) included depreciation, insurance, and return on capital

$$Fc = d + i + r \qquad \text{Eq. 1}$$

where;

d: depreciation,

i: insurance (3.5% of equipment value) (Wenger, 1984),

r: return on capital (10% rate of interest with annual equipment value (Wenger, 1984),

and Depreciation (*d*) is the losses of the machine value over time until salvage value (Miyata, 1980).

$$d = \frac{p - s}{n} \qquad \text{Eq. 2}$$

where;

p: equipment purchase cost (Machine Finder, n.d.; Finning, n.d., Truck Paper, n.d.),

s: salvage value (varies from machines to machines) (Akay, 1998),

n: expected economic life (varies from machines to machines) (Akay, 1998).

Labour cost was calculated both for summer and winter separately despite the ownership cost, which was calculated annually. Even though many operators are also owners of equipment, we used labour cost (Lc) to calculate logging cost. *Lc* is the sum of the wages paid to the operators on an hourly basis in one season (winter/summer) and converted to the unit price ($\$/m^3$) (Miyata, 1980),

$$Lc = (hr_s\, w) + (hr_o\, w_o) + el \qquad \text{Eq. 3}$$

where;

hr_s: seasonal (summer or winter) work hours, *w*: wage (Alberta Alis, n.d.),

hro: overtime worked hours. Logging industry workers are entitled to get paid overtime after 10 h of work in a day (Government of Alberta, 2018),

wo: overtime wage,

el: employee load (accounts for benefits) (Alberta Alis, n.d.).

Operation costs changes depending on production and usage. Similar to labour cost, operation cost (*Oc*) was also calculated for each logging season. Operation cost was summed up for all machines and included maintenance and repair cost (includes spare parts), fuel and oil costs.

$$Oc = mr + f + ol. \qquad \text{Eq. 4}$$

where;

mr: maintenance plus repair cost was estimated as a percentage of depreciation cost for each season (Wenger, 1984),

f: fuel cost for each machine (Kenny, 2000; Smidth & Galagher, 2013),

ol: oil plus lubricant cost (Wenger, 1984).

Even though a machine was not used during the season, if it sat idle, the ownership cost was still paid. Ownership, labour and operation costs were converted to the unit cost ($\$/m^3$) by dividing each cost to the productivity (m^3/Pmh) and seasonal production hours. The total cost of each harvesting operation (*Hc*) was the sum of the ownership cost, labour cost and operation cost.

$$Hc = \frac{Fc}{pd\ hr_a} + \frac{Lc}{pd\ hr_s} + \frac{Oc}{pd\ hr_s} \qquad \text{Eq. 5}$$

where;

pd: productivity m^3 per hours,

hra: annual production hours,

hrs: seasonal production hours (i.e., winter vs summer).

Input data section of the model also calculated number of the machines (Ne) need for scheduled production for both summer and winter logging seasons. The total number of machines was determined based on the winter logging requirements, which had a higher number of machines needed than for the longer summer.

$$Ne_{(x)} = \frac{\frac{pr_{(x)}}{de_{(x)}}}{pd_{(x)}\ hr_{(x)}} \qquad \text{Eq. 6}$$

where;

x represents logging season (i.e., summer or winter)

pr: total scheduled production volume for each season (m^3),

de: eligible harvesting/logging days (shut-down days – Sundays and statuary holidays subtracted from total logging days).

The hauling truck productivities, Eq. 7, (for two scenarios) and costs were calculated in a different sheet (Appendix A.9 and Appendix A.10).

$$pd_t = \frac{c}{\frac{h_d}{s_l} + \frac{h_d}{s_u} + \frac{t_l + t_u}{60}} \qquad \text{Eq. 7}$$

where;

pd_t: hauling truck productivity (m^3/hr),

c: capacity of hauling truck (m^3) (Alberta Transporation, 2015),

h_d: hauling distance,

s_l: average speed of loaded hauling truck (Dratchev, n.d.),

s_u: average speed of unloaded hauling truck (Dratchev, n.d.),

t_l: loading time in minutes (Machine Finder, n.d.),

t_u: unloading time in minutes (Machine Finder, n.d.).

c differs for non-frozen and frozen conditions, based on weight limits from Alberta Transportation.

2.3.7. Hauling to the Mill and Satellite Yards

Two criteria were used to govern the use of satellite yards. First, the flow of wood to the mill during winter was maintained at the minimum daily wood requirements of the mill. Second, given the flow to the mill, we adjusted the hauling volume to the mill or satellite yards to minimize the number of idle hauling trucks over the entire year, and this was sensitive to the length of the winter season.

2.3.7.1. Input Data

The total harvest volume of the base year is 2.25 million m^3. Therefore, we set the daily mill production capacity to 6,164 m^3 for the purpose of providing enough wood to the mill. Wood hauled to satellite yards was planned to be hauled to the mill during the summer and shut-down seasons. The average haul distance between cutblocks and the mill was 250 km, with 8 hours of cycle time. The distance between cutblocks and the satellite yard was 40 km, with 2 hours of cycle time.

2.3.7.2. Model Formulation

The cost of logging calculations for this scenario was similar to hauling to the mill only, except that the proportion of wood moved directly to the mill or satellite yard was adjusted to minimize idle hauling trucks. We used the Generalized Reduced Gradient (GRG) algorithm in the Excel solver to find minimum number of hauling trucks by adjusting harvest volume. GRC searches a point where the slope of the objective function is zero while changing decision variables (Winston, 2011).

The downside of this method is that the algorithm is highly dependent on the initial conditions and may not be the optimum global solution. However, in this problem, the algorithm reached the global optimum solution, which was the minimum number of idle hauling trucks (Nh) possible.

The form of the objective function is as follows:

$$\text{Min } N_h = \left(Ne_{(s)} - (Ne_{(wm)} + Ne_{(wy)})\right) \qquad \text{Eq. 8}$$

where;

$Ne_{(s)}$: number of the hauling trucks for summer hauling.

$$Ne_{(\mathrm{s})} = \frac{\frac{pr_{(s)}}{dh_{(s)}}}{pd_{t(s)}\ hr_{(s)}} \frac{1}{nt_{(s)}} \qquad \text{Eq. 9}$$

where;

$pr_{(s)}$: production volume for summer hauling (m^3),

$dh_{(s)}$: eligible hauling days,

$pd_{t(s)}$: productivity of hauling truck for summer hauling (m^3/hr),

$hr_{(s)}$: work hours per day in summer hauling season,

$n_{t(s)}$: number of trips to the mill in a day of summer hauling season,

$Ne_{(wm)}$: number of the hauling trucks for winter hauling to the mill.

$$Ne_{(wm)} Ne_{(\mathrm{wm})} = \frac{\frac{pr_{(wm)}}{\mathrm{dh}_{(wm)}}}{pd_{t(wm)}\, hr_{(wm)}} \frac{1}{nt_{(wm)}} \qquad \text{Eq. 10}$$

where;

$pr_{(wm)}$: production volume for winter hauling to the mill (m^3),

$dh_{(wm)}$: eligible hauling days for winter hauling to the mill,

$pd_{t(wm)}$: productivity of hauling truck winter hauling to the mill (m^3/hr),

$hr_{(wm)}$: work hours per day in winter hauling to the mill,

$n_{t(wm)}$: number of trips to the mill in a day of winter hauling season,

$Ne_{(wy)}$: number of the hauling trucks for winter hauling to the satellite yard.

$$Ne_{(wy)} = \frac{\frac{pr_{(wy)}}{dh_{(wy)}}}{pd_{t(wy)}\, hr_{(wy)}} \frac{1}{n_{t(wy)}} \qquad \text{Eq. 11}$$

where;

$pr_{(wy)}$: production volume for winter hauling to the satellite yard (m^3),

$dh_{(wy)}$: eligible hauling days for winter hauling to the satellite yard ,

$pd_{t(wy)}$: productivity of hauling truck winter hauling to the satellite yard (m^3/hr) ,

$hr_{(wy)}$: work hours per day in winter hauling to the satellite yard,

$n_{t(wy)}$: number of trips to the satellite yard in a day of winter hauling season.

The number of the trips, $n_{t(x)}$ calculated as follow:

$$n_{t(x)} = \frac{hr_{(x)}}{t_{h(x)}} \qquad \text{Eq. 12}$$

where;

x represents delivery location and season (i.e., wy- delivered satellite yard during the winter, wm- delivered mill during the winter, s- delivered mill during the summer)

t_h: total time to haul

2.4. Results

In the 2015–2016 logging season, we estimated 12 hauling shut-down days with a maximum temperature above 6 °C (Table 2.1). There were 151 days in the winter period between November 1st and March 31st. Subtracting the freeze-up period of November, there were 121 possible days for cutting and hauling. Furthermore, there were 29 days of Sundays and other days leaving a total of 80 workdays for hauling and 83 workdays for harvesting. The summer logging season was 214 days, which includes 61 days for break-up and bird nesting restriction. After the break-up days (61 days), Sundays, and holidays (37 days) were removed, 116 days remained for the summer logging season. A further 10 shut-down days for the summer season were removed for expected heavy rain when soil and road access would be damaged by logging machines. This leaves 106 days for summer logging.

Table 2.1 Average projected shut-down days from the HadGEM2-ES model with five time intervals and three radiative forcing values for future projections by month, with Sundays and holidays removed.

Time Intervals	Scenarios	November	December	January	February	March	Total [1]
1995–2015	Historical	3	1	1	2	8	12
2015–2016	Current	3	1	2	2	7	12
2020–2039	RCP 2.6	2	1	1	4	14	20
	RCP 4.5	2	3	1	4	15	23
	RCP 8.5	2	3	1	3	15	22
	EXT.Year[2]	3	2	3	7	23	35
2040–2059	RCP 2.6	3	3	3	4	15	25
	RCP 4.5	5	2	3	7	18	30
	RCP 8.5	3	2	3	9	19	33
	EXT.Year[2]	2	0	4	14	26	44
2070–2089	RCP 2.6	2	2	2	7	20	31
	RCP 4.5	4	3	4	7	21	35
	RCP 8.5	6	5	6	12	25	48
	EXT.Year[2]	9	8	13	13	27	61

[1] Total number of the days represents total shut-down days for the winter hauling season (December 1 to March 31). [2] EXT. Year represents the winter with the highest average winter temperature (extreme warm year) among the various climate scenarios for each time intervals. RCP, Representative Concentration Pathways.

2.4.1. Future Predictions

Average shut-down days between 2020 and 2039 were estimated to be 20 days under the climate scenario of RCP 2.6, 23 days for RCP 4.5 scenario and 22 days for RCP 8.5. Hauling shut-down days in 2040 – 2059 were expected to be 25 days with RCP 2.6, 30 days with RCP 4.5 and 33 days with RCP 8.5. Hauling shut-down days in the 2070 – 2089 were estimated to be 31 days under the scenarios of RCP 2.6, 35 days under RCP 4.5, and 48 days for RCP 8.5 (Table 2.1). These data indicate that the largest increase in shut-down days will occur in March. On the most extremely warm year of the 2070 – 2089period, there will be many shut-down days, even in midwinter.

2.4.2. Estimated Logging Cost

2.4.2.1. Hauling to the Mill Only

The harvesting with hauling cost of the base year was 20.72 $\$/m^3$ for the summer season and 18.66 $\$/m^3$ for the winter season; the logging costs (harvesting, hauling, road building, decompaction, and planting costs) were 22.95 $\$/m^3$ for the summer season and 19.51 $\$/m^3$ for the winter season. Table 2.2 shows the unit prices of logging for the base year harvesting plan (2015–2016). Machine requirements and costs of operation were specific for winter and summer conditions. The total logging cost was affected because of the idle equipment cost increases. Around one-third of machines used during the winter logging season of the base year were calculated to be idle during the summer. In the future, up to four-fifths of the machines might be idle based on the climate predictions.

Table 2.2 Unit prices for each phase of the logging operations in 2015 – 2016 with hauling directly to the mill.

Function	Summer	Winter
Felling ($/m^3$)	3.12	3.11
Skidding ($/m^3$)	3.09	3.08
Delimbing ($/m^3$)	4.25	4.29
Loading ($/m^3$)	2.05	2.06
Hauling ($/m^3$)	8.21	6.12
Cost of Harvesting and Hauling ($/m^3$)	20.72	18.66
Decompaction cost ($/km)	1143	0
Clearing/Piling cost ($/km)	3557	2124
Planting ($/ha)	1078	0
Total unit cost of logging ($/m^3$) [1]	22.95	19.51

[1] The total unit cost of logging (m^3/ha) consists of total harvesting cost (felling, skidding, delimbing, loading), hauling cost, decompaction cost, clearing/piling cost, and planting/seedling cost divided into seasonal harvest volume.

Using the cost calculator and shut-down days in Table 2.1, the various components of logging costs were estimated for the future scenarios (Figure 2.2). The cost and number of idle machines are shown more clearly in Figure 2.3.

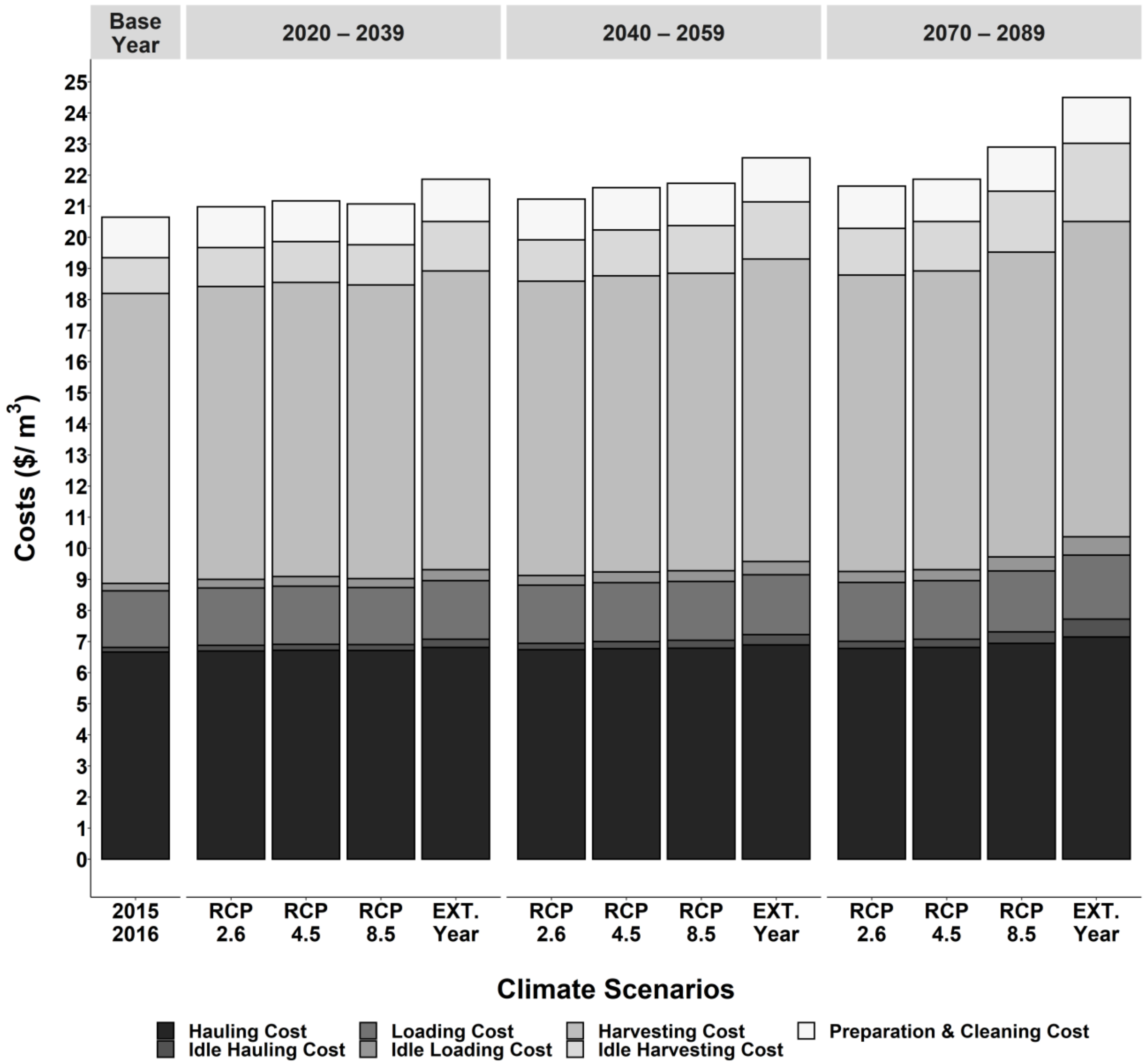

Figure 2.2 Total costs of logging operations (winter and summer) where the harvested wood is hauled only to the mill yard under the current climate and several future times with three different climate radiative forcing values, using the HadGEM2-ES climate model. The extreme year (EXT. Year) has the warmest winter in any of the RCP values of a time interval. Calculations subtracted Sundays and holidays from time available for operations.

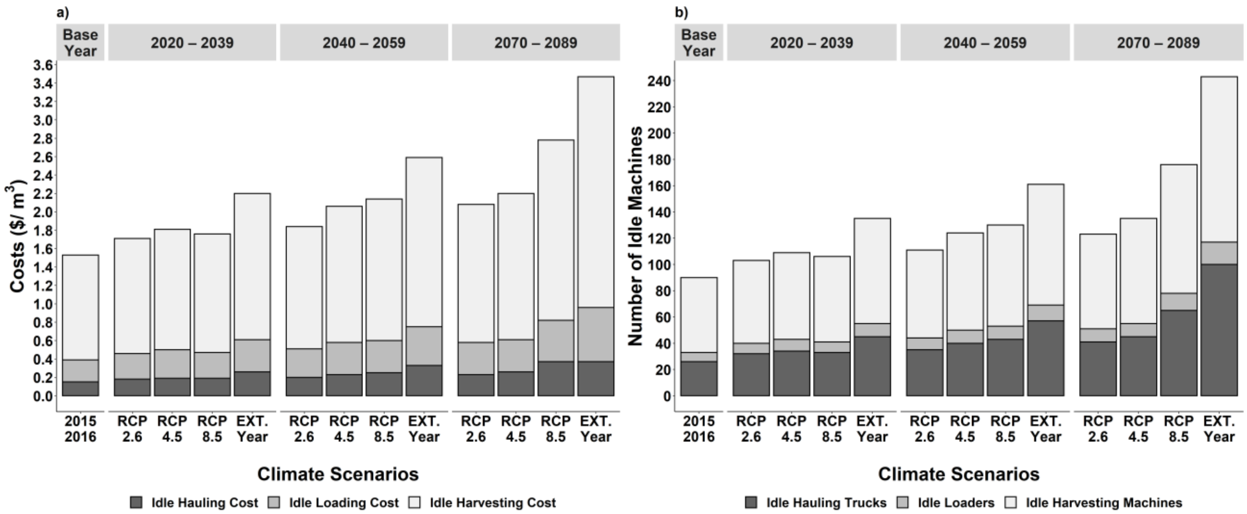

Figure 2.3 Analysis of idle logging equipment when logs were hauled only directly to the mill in winter, under different climate scenarios in several different times in the future: a) total costs of idle machines; and b) total number machines that are idle in summer months. Sundays and holidays were subtracted from the available time for operations**.**

2020 – 2039 Predictions:

The total average unit logging cost ($/m^3) is expected to increase between 2% and 3% among the various scenarios compared to the base year (Figure 2.2), using the days available for harvesting/hauling (shut-down days, Sundays and statuary holidays subtracted from total logging days at Table 2.1). The main increase was from the increase in idle equipment and the costs of harvesting, loading, and hauling (Figure 2.3). The total idle equipment cost was 1.81 $/m^3 for the RCP 4.5, the warmest scenario for the 2020 – 2039, which was a 0.28 $/m^3 increase over the 2015 – 2016 idle costs. The idle hauling truck costs rose by 27%, 15% for harvesting, and 29% for loader costs, and there was an 18% increase in the total idle costs for the entire operation (Figure 2.3). In the extreme warmest year (of this time interval), the total logging costs will be increased by 6% in the 2020 – 2039and most of this was related to the need for more equipment during the shorter period of winter logging (a 44% increase compared to the base year), hence the high annual idle costs.

2040 – 2059 Predictions:

The total unit logging cost is expected to increase between 3% and 5% among the various scenarios, compared to the base year (Figure 2.2). The total idle equipment cost was 2.14 $\$/m^3$ for the RCP 8.5, the warmest scenarios for 2040 – 2059, 0.61 $\$/m^3$ more than the base year. The idle equipment costs increased by 67% for the hauling trucks, 35% for harvesting, 46% for the loaders, and 40% for the entire logging operation (Figure 2.3). In the extreme warmest winter of the 2040 – 2059 period, the idle equipment cost was increased by 69% and the total logging cost increased by 9%.

2070 – 2089 Predictions:

The total unit logging cost is expected to rise between 5% and 11% among the various scenarios compared to the base year (Figure 2.2), using the shut-down days (Table 2.1). The main contribution to this increase was in idle equipment costs of harvesting, loading, and hauling. The total idle equipment cost for the RCP 8.5, the warmest scenario for the 2070 – 2089 was 2.78 $\$/m^3$, which was 1.25 $\$/m^3$ more than the base year. The idle equipment cost was 147% higher for trucking, 72% for harvesting, 88% for loaders, and 82% for the entire logging operation (Figure 2.3). In the extreme warmest winter of the 2070 – 2089period, the total logging cost was increased by 19%, and there was a 140% increase in idle equipment.

2.4.2.2. Hauling to the Mill and Satellite Yards

When we adjusted the winter hauling volume to the minimum annual idle hauling trucks, there was an increasing percentage of total winter logging volume that was diverted to satellite yards (Figure 2.4) in warmer winters. Of the 1,500,000 m^3 harvested in winter in the extreme year, only 510,157 m^3 might be hauled directly to the mill; the remainder would be stored in satellite yards.

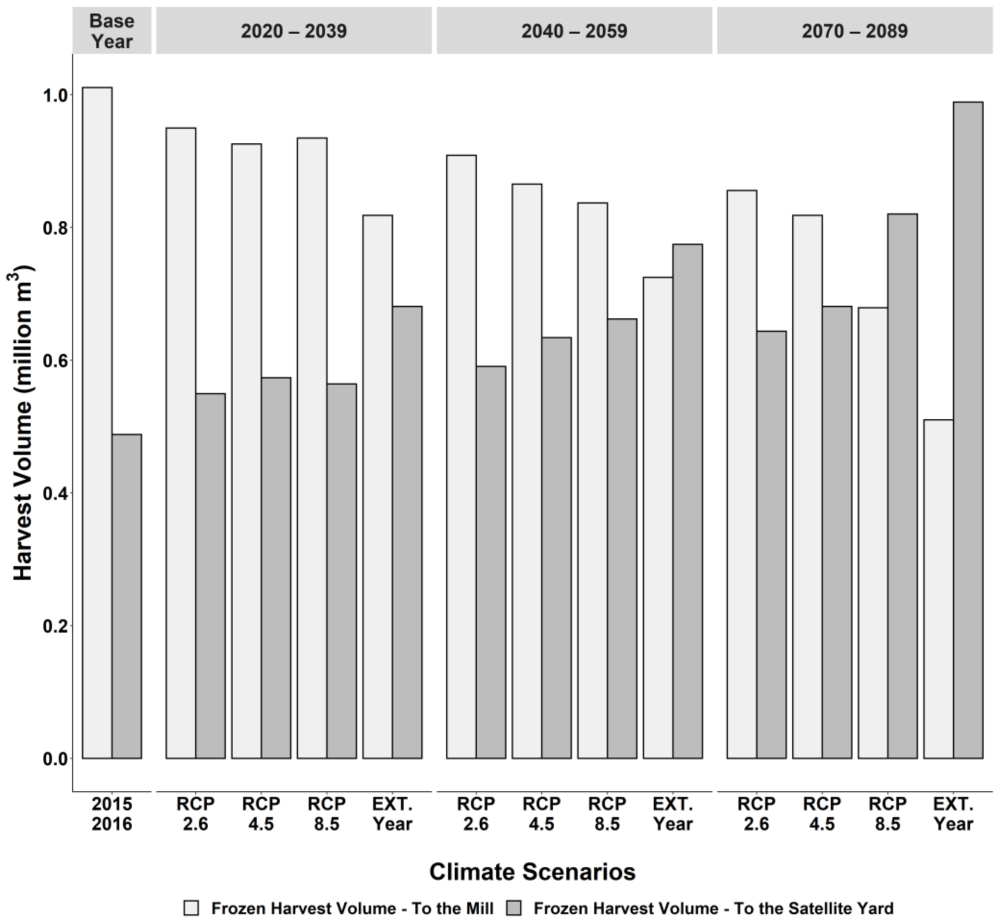

Figure 2.4 Use of satellite yard to distribute winter harvest volume of wood (m^3) with the criteria to minimize the total number of idle hauling trucks over the entire year under different climate scenarios at different time intervals.

2020 – 2039 Predictions:

The unit logging cost was expected to increase between 2% and 3% among the various scenarios compared to the base year (Figure 2.5) using the reduced number of days available for harvesting and hauling (shut-down days, Sundays and statuary holidays subtracted from total logging days at Table 2.1). The main contribution to this increase was in the idle equipment costs of harvesting and loading (Figure 2.6); hauling costs also went up, but were related to the increase in number of loads hauled to the mill at summer weights. With the use of satellite yards, 35 hauling trucks (winter plus summer) were needed, compared to 55 hauling trucks for hauling exclusively to the mill for the RCP 4.5 (Figure 2.6), which was actually a warmer scenario than the RCP 8.5 for the 2020 – 2039. The use of satellite yards also required an extra loading-unloading cycle in the winter and more annual idle loader costs. The total idle equipment cost was 1.52 $\$/m^3$ for RCP 4.5 (Figure 2.6), which was 0.21 $\$/m^3$ more than the base year. The idle harvesting machine costs rose to 15% and 24% for loaders, while the idle hauling truck cost remained zero and there was a 16% increase in the total idle cost for the entire operation. The extreme warmest year (among the three radiative forcing values) shows that the total cost was increased by 6% and the total idle equipment cost will increase by 40%.

2040 – 2059 Predictions:

The unit logging cost was expected to increase between 3% and 6% among the various scenarios (Figure 2.5), compared to the base year using the days available for logging (shut-down days, Sundays and statuary holidays subtracted from total logging days at Table 2.1). With the use of satellite yards, 40 hauling trucks (winter plus summer) were needed, compared to the 64 hauling trucks for hauling exclusively to the mill for the RCP 8.5, the warmest scenario for the 2040 – 2059. The use of satellite yards required an extra loading-unloading cycle and a higher idle loader cost. The total idle equipment cost for the RCP 8.5, the warmest scenario for the 2040 – 2059, was 1.78 $\$/m^3$, which was 0.47 $\$/m^3$ more than the base year. The idle harvesting machine costs rose to 30% and 41% for loaders, while the idle hauling truck cost remained zero (Figure 2.6). There was a 36% increase in the total idle cost for the entire operation. The extreme warmest year (among the three radiative forcing values) shows that total costs will increase by 10% and total idle equipment cost increased by 62%.

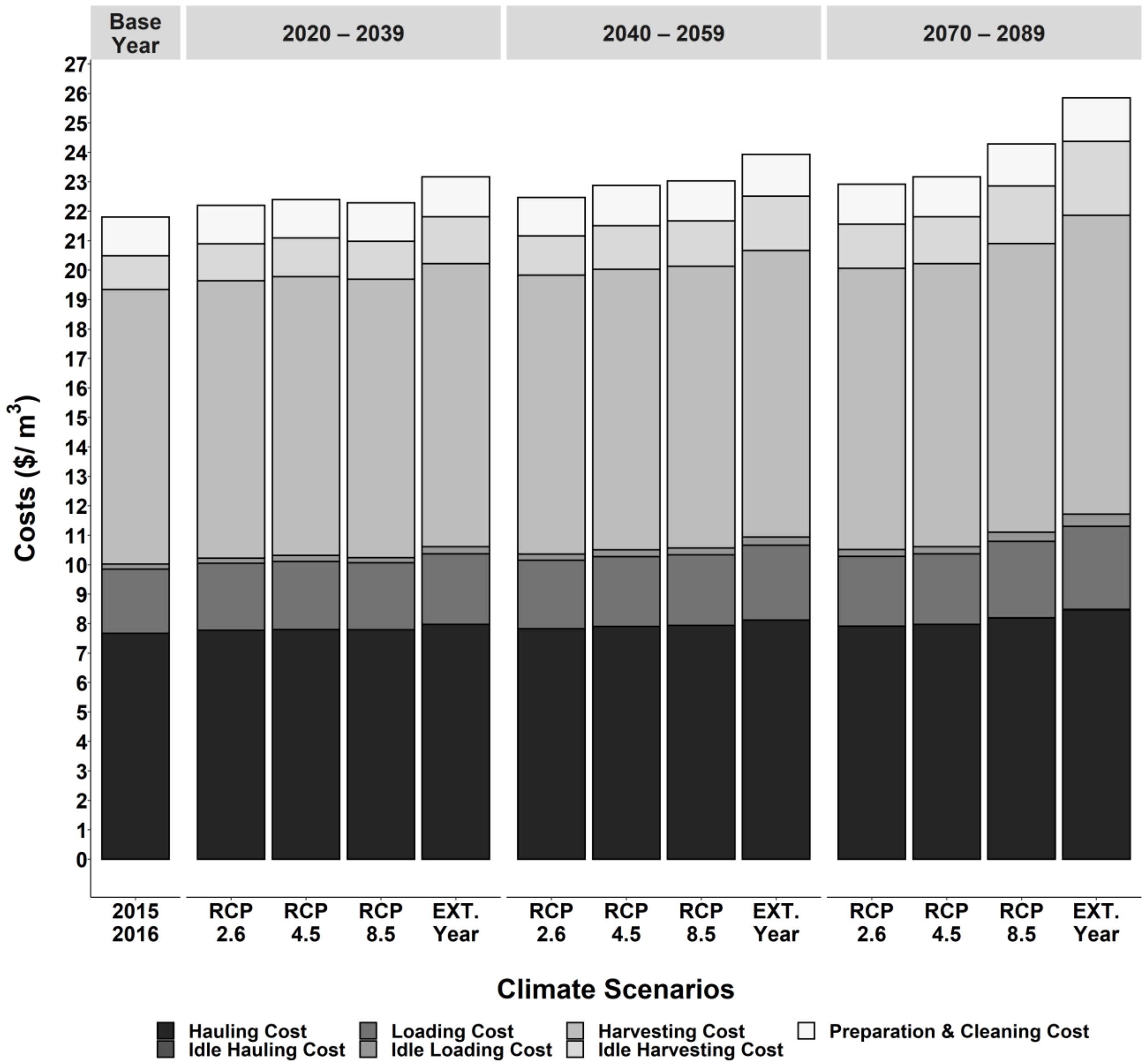

Figure 2.5 Total costs of logging operations (winter plus summer) where the harvested wood is hauled to both the mill and satellite yards under the current and several future intervals. The extreme year (EXT. Year) has the warmest winter in any of the RCP values of a time intervals. The normal Sundays and holidays were not available for operations. Note that there was almost no idle hauling cost in this analysis except RCP 8.5 and the extremely warm year of the 2070 – 2089.

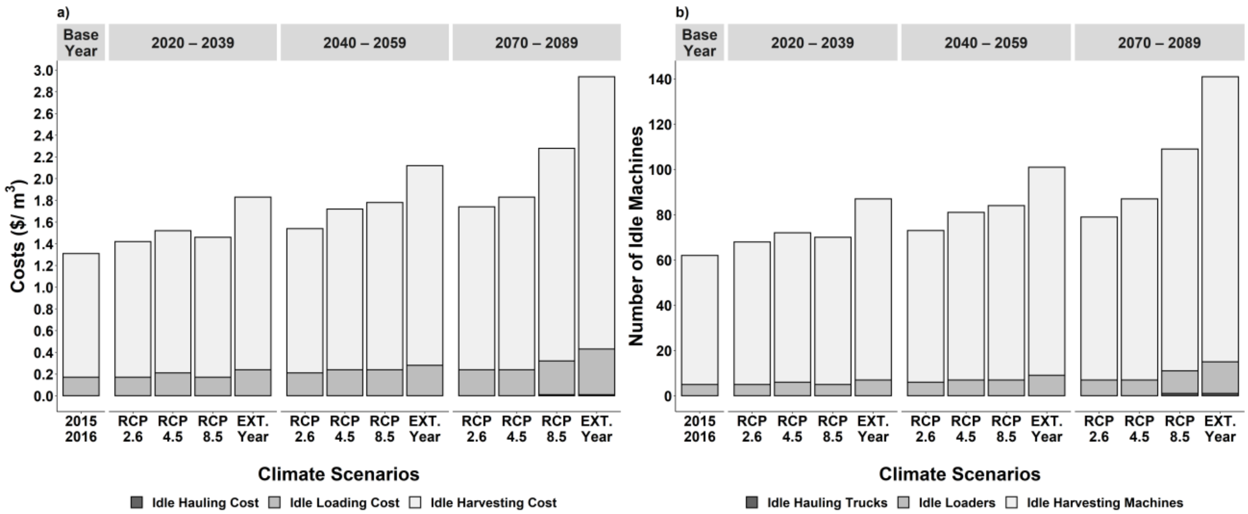

Figure 2.6 Analysis of idle logging equipment when logs were hauls both to the mill and satellite yards in the winter, under different climate scenarios in several different time in the future: a) total unit cost of idle machines that are not operated in summer; and b) total number of machines that are idle in summer months. Sundays and holidays were subtracted from the available time for operations.

2070 – 2089 Predictions

The unit logging cost was projected to increase between 5% and 11% among the various scenarios (Figure 2.5) compared to the base year—using the days available for logging (shut-down days, Sundays and statuary holidays subtracted from total logging days at Table 2.1). With the use of satellite yards, 45 hauling trucks (winter plus summer) were needed, compared to 88 hauling trucks for hauling exclusively to the mill for the RCP 8.5, the warmest scenario for the 2070 – 2089. Use of satellite yards required an extra loading-unloading cycle and higher idle loader costs. The total idle equipment costs for RCP 8.5, the warmest scenario for the 2070 – 2089period, was 2.28 $/m^3, which was 0.97 $/m^3 more than the base year. The idle equipment cost was 72% higher for harvesting and 82% higher for loaders, while there was one idle hauling truck (Figure 2.6) and a 74% increase in the total idle cost for the entire operation. In the extremely warmest winter of the 2070 – 2089period, the total logging cost was increased by 19% and there would be a 124% increase in idle equipment.

Sundays and holidays were 37 days for the summer season and 29 days for the winter season for the current time and in future scenarios. It is feasible that a forest company may not have these labour restrictions in the future, so if these days were used for logging activities and included in the cost calculations, future predicted logging cost increases could decline from 3% to 2% for the 2020 – 2039 time intervals, from 5% to 3% for the 2040 – 2059, and from 11% to 7% for the 2070 – 2089, for the analysis of hauling to the mill only. The logging cost increases compared to the base year could decline from 6% to 3% for the 2020 – 2039, 9% to 5% for 2040 – 2059, and from 19% to 9% for the 2070 – 2089 for the extreme warm winter.

For the analysis of hauling to the mill and satellite yard, if Sundays and holidays were included to the operation days, logging cost increases decline from 3% to 2% for the 2020 – 2039, from 6% to 4% for the 2040 – 2059, and from 11% to 8% for the 2070 – 2089. The logging cost increases compared to the base year declined from 6% to 4% for the 2020 – 2039, 10% to 5% for the 2040 – 2059, and from 19% to 10% for the 2070 – 2089 for the extreme warm winter.

Ice roads might be particularly damaged by shut-down days that are back to back. In the extreme winter of each time period, we counted the number of times that the shut-down occurred for two or more consecutive days of the 121 eligible loggings days (including Sundays and holidays). There were six shut-down intervals in the extreme year of the 2020 – 2039, eight intervals for the 2040 – 2059 and 12 intervals for the 2070 – 2089.

2.5. Discussion

2.5.1. The Change of the Logging Cost

This study shows that given a range of different greenhouse gas radiative forcing values, influencing winter temperatures, a medium to large company operating in the boreal forest will have a 5% to 11% increase in logging costs by the 2070 – 2089 period, using current logging strategies. These analyses are likely relevant to other companies in the boreal forest where there is a reliance upon frozen ground conditions for logging operations.

In order to complete logging operations of the sites where there is a dependency on frozen conditions, forest companies would need to use more machines and workers. This strategy, however, reduces the annual efficiency of these machines, as the extra machines will be idle during the summertime because wood volume harvested in the summer season is less than the winter season. We projected that nearly twice as many machines would need to be purchased in the average year of the RCP, forcing values of 8.5 in the 2070 – 2089when hauling is directly to the mill. Ownership costs of idle equipment in the summer months will increase by 82%, and this will account for most of the increment in the annual costs of logging. The equipment needs will be even higher during the extreme warm years of the decades surrounding 2080. If companies plan for the contingency of an extremely warm winter, equipment needs would more than double and ownership costs of idle equipment would increase 140% in the 2070 – 2089, if the company made the long haul from the logging sites directly to the mill yard. We expect that there would need to be more strategies developed for a company to cope with a very warm winter, either through more machines, stockpiling wood, or removing wood and machines from the most remote location first in frozen months.

As the hauling cost is a large component (~30%) of total logging costs, satellite log storage yards close to the logging site and close to the main road could be used to minimize the number of idle hauling trucks and unit costs of logging as a result of shorter winters. Late in the century, more than half of the wood might be stored in satellite yards during the winter season. The use of satellite yards, however, has increased the number of hauling trucks in summer (at smaller loads) and additional unloading/loading costs. Use of satellite yards, however, had little influence on the total idle equipment costs of the machines cutting, processing, and loading wood within the harvest locations; note that this is coupled with idle workers. The use of satellite yards increases the total logging costs by 1.34 $\$/m^3$ for the 2070 – 2089compared to hauling the mill only, but the idle truck and loading decreased by 0.50 $\$/m^3$ for the 2070 – 2089, compared to hauling the mill. Satellite yards, however, give feasible solutions to uncertain extreme weather changes, so forest companies can plan logging operations on a year to year basis. Satellite yards also allow deliveries to the mill during the break-up season in April, during the nesting times of birds, and during wet periods in summer. Furthermore, the hauling trucking fleet has nearly full-time employment and these stable workers will likely result in a more skilled and efficient hauling trucking workforce. Skilled truck drivers are necessary (Mitchell et al., 2008) to operate very large log trucks (up to 88,000 kg gross vehicle weight) on public highways. Such stable opportunities for work would also allow the forestry firm to compete with other opportunities for these highly skilled drivers. Satellite yards also allow the use of smaller, cheaper and more off-highway suitable trucks for a short distance hauling from logging sites to storage yards. This will allow the construction of lower standard off-highway roads in summer and winter, especially when winter roads break-up because of the temperature increases, managers may use satellite yards exclusively to empty the logging sites, and store the wood. The large hauling trucks can then be used from the satellite yards beside highways, for the longer distances to the mill, thus maximizing their production.

Given the fewer frozen days, there will be sustained pressure to work on all available days. There will, however, be inconsistent employment for the non-hauling aspects of logging, resulting in more temporary and less experienced workers. Less experienced harvesters would make felling and skidding operations less efficient in terms of machine productivity, likely reduce log quality, and be more likely to damage soils and residual trees as well as increased accidents. Lastly, periods of thaws in winter would further add to the intermittent nature of work in the winter months, which would make retention of a skilled harvesting workforce problematic.

2.5.2. Other Strategies

As our modelling results from the 2020 – 2039 and 2040 – 2059 show, with a gradual increase in the period of winter thaw, there will be time for business adaption to shorter winter periods. In early fall, lighter machines can be used for snow compaction to speed up frost penetration deep into the roadbed in November, before the harvesting starts. These types of machines may only be required occasionally, so the additional idle costs of ownership would further increase logging costs (Johnston et al., 2008). We anticipate that harvesting and hauling operators will become even more conscious of diurnal swings in temperature. Many days in mid-winter with daytime thawing have cold nights where soils might be refrozen by midnight; this would allow a shift to machine activity during the night and early morning. In discussion with forest companies, hauling in March is shifted mostly to nighttime and morning, thereby taking advantage of the nighttime freezing time. There may be adaptations to minimize soil disturbance on wet soils, such as specialized equipment, wider and low-pressure tires with high flotation, and using logging slash on the skidding tracks to limit soil disturbances. Forest companies already using central tire inflation (CTI) system that allows trucks to deflate their tires. The reduced tire pressure increases the tire footprint on the temporary roads resulting better flotation and extended access into the sites with soft subgrades (Sturos, 1995). Moreover, satellite yards allow the use of smaller, cheaper and more off-highway suitable trucks for a short distance hauling from logging sites to storage yards thus damaging temporary roads can be minimized. There is a possibility that futuristic logging technologies may reduce or eliminate the soil damage that equipment and hauling trucks cause (MacDonald, 1999). Further, building more permanent roads would help with accessibility to harvest areas (Johnston et al., 2010); however, such roads are an order of magnitude more expensive to build, and some governments limit the number of permanent roads to protect other values of forest lands.

2.5.3. The Change in the Winter Season

The climate model indicates that March is most likely to be lost as a useful month for winter logging by the 2070 – 2089 (Table 2.1) and companies would likely not plan for frozen conditions during this time if the 6 °C temperature was used as the threshold for shut-down. The month of February shows more shut-down days than November. November is predicted to remain more stably cool in the future. This likely relates to the short period of daylight and low solar angle in November, which is nearer to the winter solstice than the month of March. We note, however, that the freeze-down of roadbeds is most rapid at very cold conditions (Bradley & Thiam, 2018), so there is still uncertainty about the completion of road building in November.

2.6. Conclusion

Using more logging equipment for a shorter period of frozen conditions in the winter under climate change will increase the logging costs; the projected costs of an average winter in the 2070 – 2089with the RCP 8.5 forcing factor will be up to 11% greater than those of today if wood is hauled directly to the mill yard and 11% greater than those of today if wood is hauled to mill and satellite yard. Most of this increase is due to the cost of idle equipment.

The use of satellite yards means that much of the long haul of logs to the mill is in the summer months, when hauling trucks are restricted to smaller loads. Use of satellite yards, however, provides steady employment for hauling truckers but the smaller loads and increased costs of an additional loading and unloading operation will counter some of the benefits above. Although there is an increased cost, we expect more use of satellite yards in the future, as they provide flexibility and annual continuity of wood supply. The harvesting workforce, however, will have less predictable conditions for employment during winter operations.

The extreme years with the warmest winters will provide enormous incentives to adapt to unstable logging conditions in winter; new techniques will need to be developed to harvest wet areas and move logs across wet expanses, such as peatlands, if frost becomes unreliable in some winters.

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Chapter 3: Cost comparison of summer and winter forest road construction in uncertain climates

3.1. Abstract

Two thirds of forest harvesting in Alberta is done during the winter season when the ground is frozen. Logging activities on the frozen ground reduces the cost of forest operations by allowing heavier loads on the roads, crossing wetlands and reducing soil disturbance, etc. Increased winter temperature and more frequent winter thaws, decreased the period of the frozen ground conditions. In order to adapt shorter winter logging, forest companies might access winter harvesting sites in summer. In this study, we examined the cost of temporary forest road construction in terms of switching logging activities from frozen to non-frozen conditions. The objectives were to calculate the costs of winter road construction for operational harvesting units with different landscape conditions and calculate the cost of summer road construction of these same winter harvesting units; variables include the length of the temporary road network, stream crossing and the amount of the corduroy road needed for wetland crossing. Then we analyzed the road construction cost changes for both winter and summer access under the base case soil wetness as well as possible different wet and dry scenarios. The results show that average cost of temporary road construction increased from 1,200 \$/km or 0.30 $\$/m^3$ in frozen condition to 5,962 \$/km or 2.14 $\$/m^3$ in non-frozen condition. The summer roading cost ($\$/m^3$) under the extreme wet scenario increased up to 15 times more than winter road construction cost under the base case scenario. If the soil moisture is reduced faster than the base case situation, cost increases on summer road construction per km were expected to be between 2 times and 7 times more than winter road construction cost.

3.2. Introduction

Forest harvesting in northern climates relies on winter frozen ground conditions to access harvesting sites, to operate within sites and transport equipment, and wood (Rittenhouse & Rissman, 2015). Frozen ground can support machine traffic on wet soils and reduce the cost of forest operations compared the summer operations (Kuloglu et al., 2019). Temporary roads in winter cost less to build because ice roads can be constructed to cross wetlands simply by icing and smoothing a frozen surface. Temporary roads built on an ice matrix also requires less reclamation and decompaction and artificial regeneration because the frozen ground protects the soil from damage. Winter roads are especially important for regions such as Alberta's boreal forest region where there are high amounts of wetland and fine-textured soils that are prone to rutting. Approximately one-third of the annual allowable cut in Alberta is harvested in the summer. Only areas with soils that are relatively well-drained, however, can be reliably accessed in the summer, and then only when soils are dry. If soils are wet, they often require the construction of expensive subgrades, made from wood, geotextile, or other material that distributes the vehicle weight.

Changing climate is expected to cause warmer weather in the winter and more variation in summer rainfall patterns (Zhang et al., 2019). This, in turn, is making the planning season of harvest even more challenging. In the winter, climate change has increased the winter temperature causing unstable frozen ground and decreased eligible days of logging operation during the winter by an average 38 days in the 2070 – 2089 period (Kuloglu et al., 2019). Increased winter temperatures will impact winter access for harvesting sites. Forest companies might decide to construct temporary roads in summer in order to reduce soil and wetland damage caused by frequent winter thaws.

The forest road types in Alberta are classified based on the frequency of use and seasons of use (Tan, 1992). The paved public highway system provides the first level of access to the forest. From the highways, permanent roads (road class I to III) provide all year use, with some restrictions on vehicle weight to minimize road damage and maintenance costs at times during spring break-up or wet periods. The highest class I roads are two-lane gravel surfaces with grades and horizontal alignment to provide reliable high-speed travel (up to 80 km/hr). Permanent roads (I-III) have a progressive reduction in standards to provide reliable access within a few tens of kilometres of natural resources, such as; harvesting areas and energy facilities. From the permanent roads, the forest industry uses temporary one-lane seasonal roads (class IV and V) for short-term use during the dry summer conditions or frozen conditions. These roads are only expected to be used for one to three seasons; they are completely removed after harvest (Alberta Forest Service & Fisher, 1985). These roads need to be reliable, but shut-downs for hauling and operations to minimize costs and environmental impact are expected during warm winter days or wet summer days.

Winter and summer roads have different construction techniques and are laid out using different strategies to minimize costs and environmental impact in the different seasons. In winter, temporary roads can be located on flooded wetlands such as shallow, open-water wetlands and marshes in order to provide winter crossing. Snow and/or ice bridges can be used to cross intermittent streams. However, wetlands with flowing subsurface water or part of flowing water system and seasonally fluctuated wetlands are avoided because such substrates are difficult to cross with winter roads (British Columbia Ministry of Forest, 2002, Ducks Unlimited Canada et al., 2014, Partington et al., 2016). In forested areas, companies only need to clear the forest, remove the top of the stumps, and build a frozen road. Also, in order to avoid clearing cost, they can take advantage of seismic lines that were built by oil and gas companies. To construct the road surface, snow is compacted and then water is normally sprayed on top to produce high strength pavement (Abele, 1990; Partington et al., 2016). It is a common practice to provide drainage flow paths before the snow melts so that erosion and soil damage can be prevented (Gillies, 2011).

Temporary summer roads, in contrast, are located on drier sites and are laid out to avoid wetlands, stream crossings, and uplands with soils that have low strength when wet. To provide access when the soils are wet, a subgrade needs to be constructed. Forestry operations use corduroy roads for crossing these wet soils and even some wetlands. Wetlands like bogs, some fens and swamps may be crossed during the non-frozen conditions (Partington et al., 2016) using corduroy roads that provide bridging effect is to distribute forces from the load (both road fill and machine traffic) and minimize damage to soil and wet areas (Sessions, 2007). Most corduroy construction uses a layer of logs, a burlap or geotextile separation layer, and capping soil that provides the road surface. The voids between the logs provide an opening for the movement of both surface and shallow subsurface water. Corduroy can be effective but at a high cost. When the harvest is complete decompaction of mineral soil areas and regeneration increases the costs of temporary summer road construction compared to winter roads. Moreover, the cost of these roads and their reliability is dependent on the summer weather rainfall patterns.

The permanent road network represents large capital investments developed over multiple years and are constructed in cooperation with other users (e.g. oil and gas sector, other forest companies). Investment in their development costs are complicated and depend on the larger regional resource availability (of several sectors) and potential long-term return on investment. By contrast, the forest industry requires temporary roads on an annual basis and accounts for the development costs of a specific harvest area. The road costs are weighed along with all other block development costs to determine if an area is economically worth harvesting. Thus, the seasonal difference in the cost of temporary roads is an important factor affecting the profitability of northern forest companies and is a constraint on the amount of landbase that can be harvested.

The objectives of this study are: 1) calculate the costs of winter road construction for operational harvesting units with different landscape conditions, especially the level of and distribution of wet soil types; 2) calculate the cost of summer road construction of these same winter harvesting units (variables include the length of the temporary road network, stream crossings, and the amount of the corduroy road needed for wetland crossing); and 3) analyze the road construction cost changes for both winter and summer access under the base case soil wetness, as well as with possible different wet and dry scenarios.

3.3. Methods

3.3.1. Study Area

The Boreal Plains, is the largest forest region in Alberta, and covers 381,711 km^2. This region supplies 47 of the 50 mills in Alberta and accounts for 28.2 million m^3/year, which is for more than 90% of Alberta's annual harvest (Environment and Sustainable Resource Development, 2017; Alberta Wood Products, 2019). The topography of this forest is level to undulating with mineral soils areas of deep surficial deposits from fine textured lacustrine and till plains. The soil types are dominated by luvisol, gleysols, brunisol, and organic soil. Bogs, fens, marshes, and shallow water cover 40% of boreal plains ecozone (Vitt et al., 1996; Natural Regions Committee, 2006). The climate is a cool continental climate with long cold winters and warm summers. The daily average temperature of summers exceeds 15 °C. While summers are short, with one or two months, winters are long and cold. The average daily temperature in winter is below -10 °C for four months or more in most boreal subregions, and below -20 °C for two months or more in the most northerly subregions. During the winter, the continental polar air mass brings in cold dry air while cool, moist air from the Pacific can be influential at any time during the year. Most of the annual precipitation is received between April and August, and the peak season of the rainfall is in July (Beckingham & Archibald, 1996; Natural Regions Committee, 2006; Alberta Environment and Parks, 2015).

3.3.2. Selection of Representative Operational Harvesting Units

We selected four operational harvesting units with total harvest area of 1641 ha; these were originally harvested during the winter logging season by a forest company. Each unit had different characteristics that encompassed the range of expected difficulties if the company would be forced to log in summer. These challenges include soil wetness of in-block and surrounding areas, a range of wetland sizes between cutting areas, distance from permanent road, and remoteness of some cutblocks. Table 3.1 shows the detailed characteristic of each operational harvesting unit. Following current practices, we aggregated units of cutblocks into operational harvesting units and treated them as a unit that is intended to be accessed during one season, established road layout, and calculated road development costs for the entire units (see below for details). For most of the units, we also reported costs based on aggregated cutblocks (subunits) that were accessed by logical road branches or road sections within the harvesting units.

The first harvesting unit (Appendix B.1) was close to a permanent road. This unit had the least amount of the wetland compared to other harvesting units. The harvesting unit-1 was mostly under the medium soil rutting and compaction hazard category (Alberta Agriculture and

Forestry, 2017). The cutblocks in the operational harvesting unit-1 were close to each other and the roading could act as a whole; therefore, we did not divide this harvesting unit into subunits. Based on the wetland types in the operational harvesting unit and soil wetness, we ranked this unit to have the easiest access during summer operations.

The second harvesting unit (Appendix B.2) was divided into two subunits. The boundary of the subunit-1 is adjacent to a permanent road so the access road length for the subunit-1 is 0 metre. The subunit-1 and subunit-2 were planned to harvest at the same time so that the forest company could reuse the in-block roads of subunit-1 to access subunit-2 in order to decrease the extra cost of road construction and maintenance. There are multiple seismic lines located in the harvesting unit-2 that could be easily frozen for winter road construction. The entry point of this harvesting unit was at the end of the permanent road. Subunit-1 in this harvesting unit was relatively dryer than subunit-2. Thus, accessing subunit-1 during summer was less costly than subunit-2. Based on the soil wetness and easy access to permanent road, we ranked this harvesting unit second easy access among the other harvesting units during summer operations.

The third harvesting unit (Figure 3.1) was divided into 3 subunits. The distance to a permanent road of the harvesting unit-3 was further than unit-1 and unit-2. All three subunits were originally assigned for winter operations by the forest company because of short easy access via seismic lines. However, in summer operations, the forest company would need to construct expensive roads to cross this wet soil or develop longer and less direct routes on drier soils. In general, wet areas were avoided in summer to minimize the amount of the corduroy roads. This harvesting unit had mixed rutting and compaction hazard units inside. The subunit-1 and subunit-2 were close to each other but did not share any boundaries. The subunit-3 in the harvesting unit-3 was planned for harvest at the same time of the year with the rest of the subunits; however, it was located a few kilometres away from the other subunits. Longer access roads were necessary to reach subunit-1 and subunit-3.

The fourth harvesting unit (Appendix B.3) represents difficult and costly access during the summer. The cutblocks in unit-4 were in a peatland matrix and were divided into three subunits. The other difference between harvesting unit-4 and other units was that the amount of the access and in-blocks road was longer than other harvesting units.

Table 3.1 Characteristic features of operational harvesting units

Harvesting units	Landform Wetland (%)	Soil type	Accessibility[1]	Rutting and compaction hazard on the summer road network[2]
Unit -1 (348 ha)	4.4% wetland 36.7% riparian 58.9% upland	84.7% moist fine loamy clay 1.1% organic 14.2% very dry/sandy	523 m for winter 537 m for summer	2% High 57% Medium 5% Low to medium 36% Low Road Network Length[3]: 16.7km
Unit - 2 (409 ha)	4.7% wetland 38.1% riparian 57.2% upland	88.4% moist fine loamy clay 2.5% organic 9.1% very dry/sandy	0 m for winter 0 m for summer	10% High 54% Medium 9% Low to medium 27% Low Road Network Length: 21.2km
Unit - 3 (572 ha)	5.5% wetland 34.2% riparian 60.3% upland	89.7% moist fine loamy clay 1.5% organic 8.8% very dry/sandy	1485 m for winter 3374 m for summer	4% High 53% Medium 21% Low to medium 22% Low Road Network Length: 28.2km
Unit - 4 (312 ha)	31.3% wetland 15.2% riparian 53.5% upland	89.7% moist fine loamy clay 10.2% organic 0.1% very dry/sandy	267 m for winter 300 m for summer	33% High 61% Medium 5% Low to medium 0% Low Road Network Length: 29.8km

1. Distance from permanent roads to closest entrance of harvesting unit.
2. Detailed rutting and compaction hazard distribution of harvesting units can be found in Appendix B.4 and on distribution on road network is in Appendix B.5.
3. Road network length is the total roading for summer access to harvesting unit; including access roads and in-block roads. Winter road and corduroy road length is in Appendix B.5.

3.3.3. Data Sources

Cutblocks, streams, lakes, and existing roads (permanent, seismic lines, and temporary roads) datasets in this study were provided by a forest company in northern Alberta. In order to draw a road network, we used topographic contour lines (Altalis, 2017). We also used Derived Ecosite Phase (DEP) mapping (Alberta Agriculture and Forestry, 2017). The DEP is a digital and spatial representation of ecological site phases in the areas where the Alberta Vegetation Inventory (AVI) and Lidar datasets are available. Alberta merged wetland inventory (Government of Alberta, 2014) classification dataset was also used to avoid wet areas for route selection. The DEP allowed the development of a road network based on soil moisture content and rutting hazard in the area (Appendix B.4) based upon soil type and the soil's drainage class or soil texture for coarse-texture soils. There are five rutting hazard categories: Low, Low to Medium, Medium, Medium to High, and High. High-hazard ratings indicate that it is unlikely that summer operations would be possible without corduroy, medium ratings indicate that operations may be possible in dry periods, while those with low-hazard ratings are good candidates for summer operations (Alberta Agriculture and Forestry, 2017). We overlaid Alberta Merged Wetland Inventory dataset (Alberta Environment and Parks, 2018) with cutblocks for route design that minimized crossing wet areas.

3.3.4. Road Network Layout

We located temporary winter and summer roads by manually digitizing routes in ArcGIS (ESRI, 2018) following a set of guidelines that represent the strategies that forest planners use (Winkler, 1998). For both summer and winter roads, we used a maximum road grade of 5%, a maximum skidding distance of 350 m, a target skidding distance of 250 m, and followed the regulation that limits the area covered by roads to < 5% of the total cutblock area (Alberta Forest Service, 1994).

Winter roads simply took the shortest path to access harvesting units and haul in the blocks avoiding only flowing water systems and soil compaction during the mid-winter thaw season. Another challenge is the compaction of the wetland soil which can disturb the subsurface water movement. Organic soil needs to be pushed and rolled back to minimize soil damage. Lack of fill material in the area can increase the road construction cost. The road location developed in this study were discussed with local operation foresters and road layout approved by these professionals.

3.3.5. Amount of Corduroy

The rutting hazard is normally used to determine the likelihood of soil damage from in-block operations such as skidding. However, in discussion with forest professionals and observations from post-harvest air photos, we noticed that the rutting hazard defined in the DEP is a good map surrogate for the soil strength and ability to support haul traffic during different wet soil conditions. We assumed that the amount of the corduroy road construction will depend on the DEP rutting hazard categories and the weather, in particular the frequency and severity of summer storms. The base case assumed corduroy was needed for 100% of the area in the high rutting hazard, 10% of medium rutting hazard, 5% of low to medium rutting hazard and 0% of low rutting hazard (Table 3.2) (note there was no medium to high rutting hazard in the study areas). No corduroy was needed in the low rutting hazard areas. Then to account for the possibility of the dryer and wetter summer conditions we changed the percentage of corduroy required in each DEP rutting hazard category (Table 3.2).

Table 3.2 The amount of corduroy roads assumptions (%) for base case and future scenarios for each rutting hazard categories

	Base Case	Wet1	Wet2	Wet3	Dry1	Dry2	Dry3
High	100	100	100	100	100	100	90
Medium	10	15	20	25	5	0	0
Low-Medium	5	10	15	20	0	0	0
Low	0	0	5	10	0	0	0

3.3.6. Road Construction Cost Calculation

Road cost was calculated for the total length of temporary roads from permanent roads to harvesting units includes both access roads and in-blocks roads. Although large watercourse crossing can be very expensive, local operations foresters noted that this was not likely a factor contributing to high costs in the landscape. Most crossings were short and modular temporary steel bridges were almost always used. The capital cost of the bridges was not accounted for because the bridges were purchased decades ago, and only the transportation and installation costs were relevant.

In order to calculate the cost of summer road construction, we developed a new road layout spatially suitable for the summer season.

The roading cost for winter consists of only road construction whilst summer road cost includes upland road construction, corduroy installation, and restoration cost of upland roads and corduroy roads.

Roading cost for winter (Rc_w) was calculated as below:

$$Rc_w = L_w \ x \ Cb_w \qquad \text{Eq. 1}$$

where;

L_w: the length of roads building on the upland. During the winter season, wet areas were considered as upland since ground was frozen

Cb_w: cost of road building. 1.2 $/m for winter road construction (Operations Forester, personal communication, Sep. 27, 2018)

Roading cost for summer (Rc_s) was calculated as below:

$$Rc_s = L_s \, x \, Cb_s + L_c \, x \, C_c + N_r \, x \, C_r + Fu + Fc \quad \text{Eq. 2}$$

L_s: the length of roads building on the upland. During the winter season, wet areas were considered as upland since ground was frozen

Cb_s: cost of road building. 1.6 $/m was for summer (Operations Forester, personal communication, Sep. 27, 2018)

L_c: length of corduroy road. Corduroy roads were only installed for summer road construction in order to cross wet areas (See section 2.5 for how the length was determined)

C_c: cost of corduroy road installation which was 12 $/m (Operations Forester, personal communication Sep. 27, 2018)

N_r: number of the stream crossing. This was also only considered for summer logging season

C_r: cost of bridge installation which was $850 (Operations Forester, personal communication Sep. 27, 2018)

Fu: restoration cost of summer upland roads. 4 hours per 1 km of reclamation is required for upland summer road (Operations Forester, personal communication Sep. 27, 2018). The reclamation hourly rate was 150 $/hr (Sessions & Sessions, 1992). Therefore, the cost of road restoration was 600 $/km.

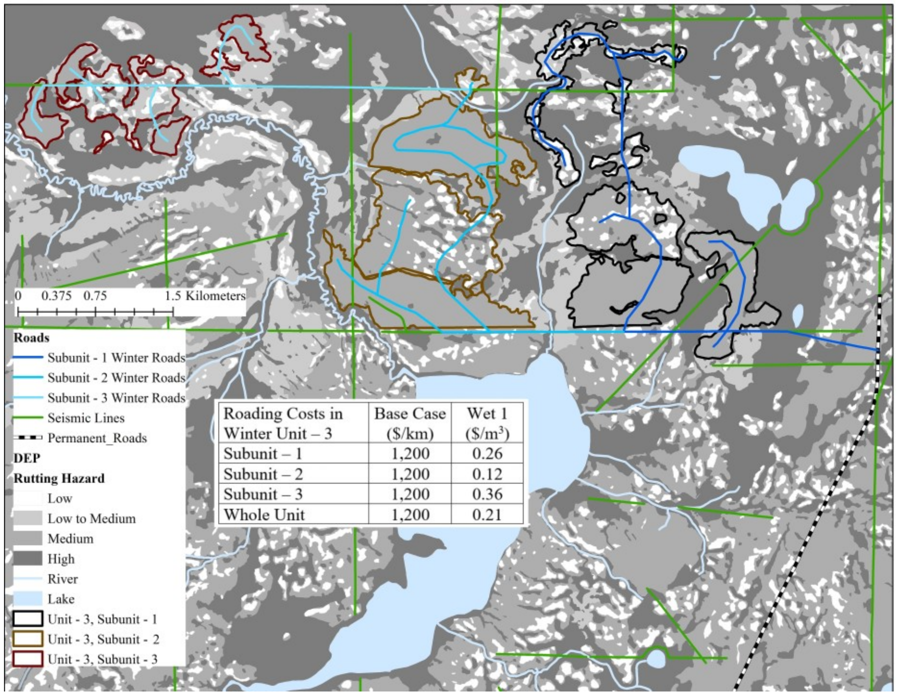
Fc: restoration costs of corduroy roads. 4 hours is required per 100 m corduroy road to reclaim (Operations Forester, personal communication Sep. 27, 2018). The reclamation hourly rate was 150 \$/hr (Sessions & Sessions, 1992). The restoration costs was 6 \$/m for corduroy roads.

We analyzed and compared the results in unit cost both for \$/km and \$/m^3. The dollar amount per kilometres was calculated as total roading cost divided into the total amount of the road length. The relative cost of road building per m^3 of wood extracted was calculated as total roading cost divided into total wood volume in the harvesting units. The average wood volume was calculated as 250 m^3/ha (JC Barlett & Asstes Ltd, 2004; Weyerhaeuser Company Ltd., 2005; Louisiana-Pacific Canada Ltd., 2016). In order to construct corduroy roads, logs were provided from the harvesting areas. 0.15 m thick and 8 m wide corduroy road would consume 1.2 m^3/m or 1,200 m^3/km. We calculated the \$/m^3 unit cost of road construction based on the remaining wood volume in the harvesting unit after subtracting the required logs used for corduroy.

3.4. Results

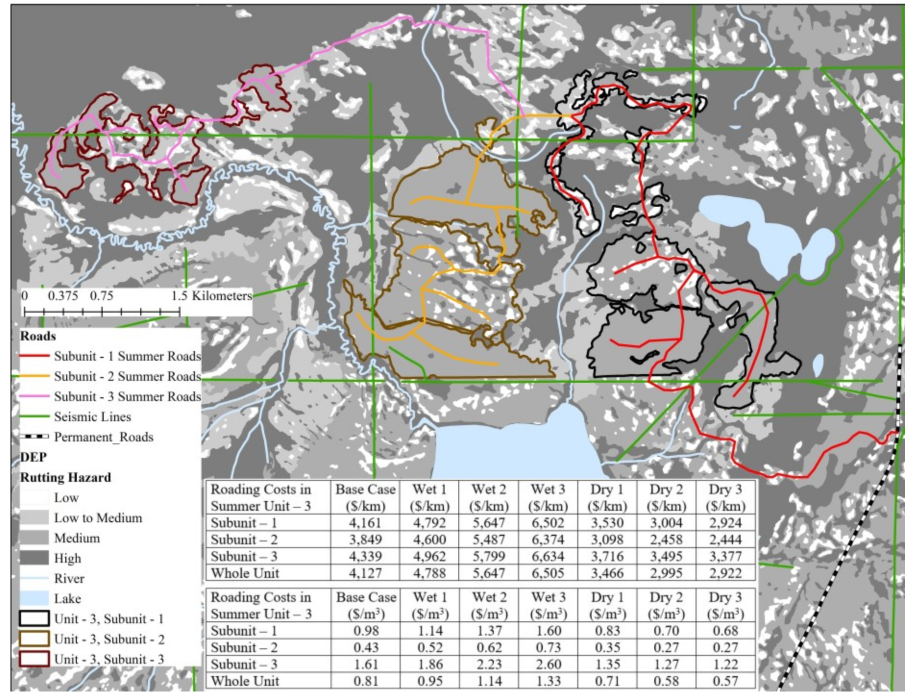
3.4.1. Additional Road Length in Summer

While discussing the cost structure of temporary roads with forest professionals we observed that cost of the temporary summer roads built on favourable soils and the winter roads are relatively stable and predictable. This is likely because the terrain in the region is flat and soils are easy to work with. For summer operations there were longer roads because of the need to minimize stream crossing and soils prone to rutting (Figure 3.1). Thus, the total length of the road required for all four harvesting units was 88 km for the winter season and 96 km for the summer season (Appendix B.5). Streams were assumed to be crossed during the frozen condition with log bundles and compacted snow when there is no flow. Stream crossing during the winter season estimated that there was no additional cost on the road construction. On the contrary, steel bridges used for stream crossing during the summer season included transportation and installation fee since forest companies re-use existing bridges. Road construction unit costs are shown in Table 3.3. Personal communication with foresters (2019) in Alberta verified that our results were aligned with their experiences.



Roading Costs in Winter Unit – 3	Base Case ($/km)	Wet 1 ($/m³)
Subunit – 1	1,200	0.26
Subunit – 2	1,200	0.12
Subunit – 3	1,200	0.36
Whole Unit	1,200	0.21

Figure 3.1.a Road network and construction cost in winter for unit-3



Roading Costs in Summer Unit – 3	Base Case ($/km)	Wet 1 ($/km)	Wet 2 ($/km)	Wet 3 ($/km)	Dry 1 ($/km)	Dry 2 ($/km)	Dry 3 ($/km)
Subunit – 1	4,161	4,792	5,647	6,502	3,530	3,004	2,924
Subunit – 2	3,849	4,600	5,487	6,374	3,098	2,458	2,444
Subunit – 3	4,339	4,962	5,799	6,634	3,716	3,495	3,377
Whole Unit	4,127	4,788	5,647	6,505	3,466	2,995	2,922

Roading Costs in Summer Unit – 3	Base Case ($/m³)	Wet 1 ($/m³)	Wet 2 ($/m³)	Wet 3 ($/m³)	Dry 1 ($/m³)	Dry 2 ($/m³)	Dry 3 ($/m³)
Subunit – 1	0.98	1.14	1.37	1.60	0.83	0.70	0.68
Subunit – 2	0.43	0.52	0.62	0.73	0.35	0.27	0.27
Subunit – 3	1.61	1.86	2.23	2.60	1.35	1.27	1.22
Whole Unit	0.81	0.95	1.14	1.33	0.71	0.58	0.57

Figure 3.2.b Road network and construction costs in summer for unit-3: base case, dry and wet scenarios

Table 3.3 Road construction unit costs (\$/km and \$/m^3) designed spatially for winter and summer in base case

		Cost (\$/km) Summer[2]	Cost (\$/m^3) Winter	Summer
Unit – 1		3,684	0.22	0.72
Unit – 2	Subunit 1	4,969	0.23	1.07
	Subunit 2	5,143	0.25	1.12
	Whole harvesting unit – 2[1]	5,054	0.24	1.10
Unit – 3	Subunit 1	4,161	0.26	0.98
	Subunit 2	3,849	0.12	0.43
	Subunit 3	4,339	0.36	1.61
	Whole harvesting unit – 3[1]	4,127	0.21	0.81
Unit – 4	Subunit 1	7,884	0.45	4.80
	Subunit 2	9,782	0.34	3.74
	Subunit 3	9,849	0.44	4.79
	Whole harvesting unit – 4[1]	9,277	0.40	4.33
Average		5,962	0.30	2.14

1. Unit costs are calculated as a whole harvesting unit without separating into subunits.
2. Winter road construction cost was \$1,200 per km for each harvesting units and subunits.

3.4.2. Cost of Corduroy

The additional length of corduroy road required was the largest additional cost and likely the deciding factor that would be used to determine the economic feasibility of a summer operation for a harvesting unit. In the analysis, the amount of corduroy road construction depends on the DEP rutting hazard categories (Appendix B.5). In this landscape the mosaic of wetlands and uplands forest make is impossible to avoid all unfavorable wet areas, even with longer roads. As a result, corduroy roads were required and significantly drove up the road construction cost. For example, harvesting unit 1 (the most suitable for easy summer access) needed 1.3 km of corduroy road for the base case that increased the access cost of this harvesting unit an additional \$24,083 (\$16,056 for installing \$8,027 for reclaiming corduroy road). In the extreme case, it appears that it is still physically possible to construct roads to access harvesting unit 4 in the summer but it is not practical or economical because 12 km of corduroy roads were required for the 30 km road network. The road development costs for summer are displayed in Table 3.3 while the costs per km for winter roads were assumed to be constant at an average of 1,200 \$/km. Roading costs in summer range from 3,684 \$/km (unit 1) to 9,849 \$/km (unit 4). The summer roading cost in terms of \$/km was calculated 3.1 times the winter road construction cost for harvesting unit 1, 4.2 times for whole harvesting unit 2, 3.4 times for whole harvesting unit 3, and 7.7 times more for whole harvesting unit 4.

3.4.3. Feasibility of Accessing Units

The roading cost in \$/km is important if our road costs are realistic, but the $\$/m^3$ is the more important metric because it will determine the economic feasibility of a harvesting unit (Table 3.3). The roading cost ($\$/m^3$) ranges between 3.3 times (unit 1) and up to 11 times in subunit-4.2 more than winter road construction. Subunit-3.2 showed that road construction cost was as low as 0.12 $\$/m^3$ in winter and 0.43 $\$/m^3$ in summer. This shows that the size of the timber basket available in the unit can determine if accessing harvesting units in the summer is feasible.

3.4.4. Variation in Summer Wetness

Table 3.4 shows the road construction cost (\$/km and $\$/m^3$) under different climate scenarios. The average summer road construction cost of four harvesting units was calculated as 5,962 \$/km. When we applied the extreme wet assumptions (Table 3.2), the average road construction costs for the four harvesting units was expected to increase to 8,046 \$/km which is 6.7 times more than winter road construction. However, under the extreme wet scenario (highest amount of the corduroy – Appendix B.6), summer road construction cost for harvesting unit-4 (most difficult summer accessibility in the study area) was 9.2 times more than winter construction. On the contrary, if the summer precipitation decreases, the summer road construction cost can decrease to as low as 2,444 $/km (subunit-3.2) as a result of less need for corduroy roads (twice that of winter road construction).

Table 3.4 Summer roading cost ($/km and $/m^3) of spatial layout for summer logging season under the base case moisture classes under increasing summer wetting (Table 3.4.a) and increasing drying (Table 3.4.b) scenarios

a. Wet Scenarios

		Base Case ($/km)	Wet-1 ($/km)	Wet-2 ($/km)	Wet-3 ($/km)	Base Case ($/m^3)	Wet-1 ($/m^3)	Wet-2 ($/m^3)	Wet-3 ($/m^3)
Unit – 1		3,684	4,236	5,112	5,989	0.72	0.83	1.02	1.23
Unit – 2	Subunit-1	4,969	5,497	6,300	6,605	1.07	1.19	1.38	1.43
	Subunit-2	5,143	5,747	6,554	7,360	1.12	1.26	1.37	1.66
	Whole Unit	5,054	5,619	6,424	6,974	1.10	1.23	1.34	1.56
Unit – 3	Subunit-1	4,161	4,792	5,647	6,502	0.98	1.14	1.37	1.60
	Subunit-2	3,849	4,600	5,487	6,374	0.43	0.52	0.62	0.73
	Subunit-3	4,339	4,962	5,799	6,634	1.61	1.86	2.23	2.60
	Whole Unit	4,127	4,788	5,647	6,505	0.81	0.95	1.14	1.33
Unit – 4	Subunit-1	7,884	8,555	9,227	9,899	4.80	5.36	5.94	6.57
	Subunit-2	9,782	10,354	10,925	11,497	3.74	4.02	4.30	4.60
	Subunit-3	9,849	10,418	10,987	11,556	4.79	5.16	5.55	5.95
	Whole Unit	9,277	9,875	10,474	11,073	4.33	4.70	5.08	5.47
Average		5,962	6,573	7,338	8,046	2.14	2.37	2.64	2.93

b. Dry Scenarios

		Base Case ($/km)	Dry-1 ($/km)	Dry-2 ($/km)	Dry-3 ($/km)	Base Case ($/m^3)	Dry-1 ($/m^3)	Dry-2 ($/m^3)	Dry-3 ($/m^3)
Unit – 1		3,684	3,132	2,622	2,585	0.72	0.61	0.50	0.50
Unit – 2	Subunit-1	4,969	4,441	4,047	3,862	1.07	0.95	0.86	0.82
	Subunit-2	5,143	4,540	3,964	3,787	1.12	0.98	0.85	0.81
	Whole Unit	5,054	4,489	4,006	3,825	1.10	0.97	0.86	0.81
Unit – 3	Subunit-1	4,161	3,530	3,004	2,924	0.98	0.83	0.70	0.68
	Subunit-2	3,849	3,098	2,458	2,444	0.43	0.35	0.27	0.27
	Subunit-3	4,339	3,716	3,495	3,377	1.61	1.35	1.27	1.22
	Whole Unit	4,127	3,466	2,995	2,922	0.81	0.71	0.58	0.57
Unit – 4	Subunit-1	7,884	7,212	6,668	6,221	4.80	4.27	3.87	3.55
	Subunit-2	9,782	9,211	8,667	8,021	3.74	3.47	3.22	2.93
	Subunit-3	9,849	9,280	8,719	8,068	4.79	4.43	4.09	3.71
	Whole Unit	9,277	8,678	8,128	7,536	4.33	3.97	3.66	3.33
Average		5,962	5,351	4,849	4,588	2.14	1.92	1.74	1.61

3.5. Discussions

This study showed that switching logging activities from frozen to non-frozen conditions will increase the average cost of temporary access and the in-block road from $1,200 per km to $5,962 per km in thawed conditions. Furthermore, the average temporary roading cost per m^3 of timber went from 0.30 $\$/m^3$ in winter to 2.14 $\$/m^3$ in the thawed condition. It should be noted, however, that the upland blocks slated for logging in this study were from a landscape where peatlands were common in the landscape mosaic. The actual roading costs to access individual units and subunits increased by distance from main haul roads and the length of wetland that had to be crossed. The prediction of shorter winters with reduced time of frozen soil conditions has been suggested to the increased difficulty of winter logging (Barrow et al., 2004; Spittlehouse, 2005; Kuloglu et al., 2019) and a shift to non-frozen conditions (Lemmen et al., 2008; Houle et al., 2009). The current study, however, is the first study to determine the change in the cost of building temporary roads if boreal forest units designated for winter harvesting were switched to non-frozen conditions.

The study shows that the cost per km of temporary summer road construction for some of the logging units for base case can be between 3,684 \$/km (unit-1) and up to 9,277 \$/km (unit-4.3). In other word, summer roading cost was at least 3.1 times more expensive but ranged up to 7.7 times that of frozen ground road construction. The cost per m^3 of summer roading, on the other hand, ranged between 0.72 $\$/m^3$ (3.3 times that of winter in unit-1) to 4.33 $\$/m^3$ (11 times that of winter for unit-4.2). The increase in summer road construction came from several sources: the need for stump removal, rollback of the organic layer, soil decompaction/road restoration, or bridges to cross streams – all of which have much more economical solutions in frozen conditions. Also, the winter road network is shorter because roads can be located directly across wetlands. In non-frozen conditions, peatlands can only be crossed by building expensive corduroy roads (see more below). In the comparison of conditions between unit-1 and unit-4, unit-1 had a 3% increase in road length and 1,338 m of corduroy road compared to a 13% increase in road length and 11,779 m of corduroy road in unit-4. The volume of wood accessible from their road network was slightly less in unit-4 than unit-1. It is therefore unlikely that unit-4 would be viewed as a possible summer logging site under the most economic conditions.

The largest cost increases resulted because of the estimated 10 times increase in cost to cross peatland in non-frozen conditions using corduroy roads. In winter, frost can be used as the subgrade to support traffic. Forestry company costs ($12 per linear m) are relatively low because they can use wood in the immediate are to construct the corduroy and only pay a low level of stumpage and felling and skidding costs to build the corduroy. Forest companies also use a burlap separation layer between logs and subsoil because it can be left on site to decompose. We think, however, that this cost of building corduroy is likely too low if long lengths of corduroy are planned. Firstly, large amounts of wood are consumed in such roads: e.g., for unit-4, with only 78,000 m^3 of timber in the unit, it would give up 18% of its wood basket to build the corduroy. This opportunity cost adds to the real cost of the use of corduroy. Second, the true cost of building very long lengths of corduroy may actually be higher than the estimated here because the entire structure has to be built from one end. Construction would be slowed by machine traffic jams where the burlap and subsoil placement would need to keep pace with the log placements in a kilometre-long building operation. Similar to installation cost, the road restoration can vary based upon its length. The local energy sector likely pays much more for their temporary crossing where they use large squares (approximately 3x3m) of laminated rough sawn lumber (thickness of approximately 15 cm) known as “rig mats” or “swamp mats”. These can be precisely laid and removed by a modified excavator, but are very expensive.

The effects of future changes in precipitation and soil wetness were linked to the proportion of the road network that would need to be shifted to or away from the need for corduroy given a wetting or drying of the landscape and a shift in rutting hazard. We considered wetter and drier scenarios as Global Circulation Models (GCMs) have predicted both increases and decreases in summer precipitation (Shepherd & McGinn, 2003; Mbogga et al., 2010; Eum et al., 2017; Murdoch et al., 2019). An increase or decrease in wetness caused a shift up or down by 30% in roading costs (Table 3.4). Confounding the issue is the fact that even with constant precipitation, increased temperature will increase evaporation and lead to declined soil wetness (Trenberth, 2011). In the end, however, the average change in summer precipitation is not likely the most important factor, but rather the severity and frequency of summer precipitation on wet or dry summers which affects the amount of time that soils are dry enough to support industrial traffic. The uncertainty of summer convective and frontal storms on some years make operations uncertain. For example, the summer of 2005 in Alberta (Alberta Transportation, 2007; Wang et al., 2016) saw frequent summer storms that prevented the soils from drying in between, which prevented travel of even light pickup trucks on most in-block roads. Finally, forest companies were required to construct a large amounts of corduroy roads across mineral soil sites greatly increasing the cost of temporary roading for that summer.

Other factors that could justify harvesting in summer relate to the amount of wood accessible from a network of access roads. For example, the unit cost of road construction in the summer base case for subunit-3.2 was 0.43 $\$/m^3$ which is lowest among the other harvesting units and subunits because of the large amount of wood available. In summer, units with significant roading costs and a small wood basket might never be cut if there was a shift to summer logging especially when corduroy roads consume much of the harvesting wood in order to cross wetlands. Once a corduroy road is built, however, it might be used for several years to access even more distant harvesting sites with timber thereby enlarging the wood basket in the summer. Timber supply analysis would help to identify available wood basket in the area for future harvesting.

The proximity of a harvesting site to permanent roads also affects the cost of temporary road construction. For example, the distance between the entry point of harvesting site 3 and permanent road during the frozen ground condition is approximately 1500 m, while this distance increases to 3400 m during the non-frozen season in order to avoid sensitive wetland crossings. Moreover, the summer access road for harvesting unit-3 was required to install corduroy road that increased the total cost of accessing this unit. Fortunately, however, unit-3 had a larger wood basket than the other units.

There may be other strategies for addressing a much shorter winter season or taking measures to reduce the costs of non-frozen road building:

First, the length of temporary roads can be reduced if skidding distance is increased. In the current study, the skidding distance was 350 m. A decrease in in-block road density and road length will decrease the road construction cost (MacDonald, 1999), but such a strategy needs to be taken only with caution, to ensure that increased skidder traffic does not damage soils or simply transfer the cost to the skidding operations. Among other things, aggregated harvests reduced the number of roads, as well as road construction costs, and the need to keep these roads open for a long period (Alberta Pacific Forest Industries Inc., 2018a). It is expected that the use of aggregated harvests will be increased in the future (Work et al., 2003) to decrease the cost. For instance, if subunit-2.1 and subunit-2.2 were not aggregated, accessing subunit-2.2 would require 3466 m additional access road and 813 m of it was corduroy road which costs 14,000 $ to install and 6,470 $ for reclaim the base case.

Second, in some cases, cost of access roads can be shared with other resource sectors. Permanent road construction associated with the energy and forestry sectors (Schneider et al., 2003; Alberta Pacific Forest Industries Inc., 2018b) could decrease the amount of temporary road needed and provide more opportunities for possible transitional cutblocks. The various energy sectors likely pay much more for their lowest grade roads because they require roads for a longer time and thus invest in stronger more expensive geotextile that lasts longer than burlap.

Third, despite a shortened winter season, the temporary winter roads might be put to their best use by the development of satellite yards as temporary log storage areas near permanent roads. In this way, trucks could quickly move the wood from the harvest units by many short haul cycles. The long hauls can be delayed until summer. However, using satellite yards increases the cost of loading/unloading and hauling (Kuloglu et al., 2019) but this would need to be balanced in comparison to building non-frozen or permanent roads. Note also, there are some provincial government restrictions on the amount of road disturbance.

3.6. Conclusion

It is expected that more harvesting will be required in the summer months (Rittenhouse & Rissman, 2015; Geisler et al., 2016); more units considered transitional (i.e., internally suitable to be harvested in either frozen or non-frozen ground conditions) will be shifted to summer which will add costs to logging in the wetland-rich areas of northern Alberta. The cost of temporary roads will increase between 3 times or more than 8 times if units were accessed in non-frozen conditions vs in frozen conditions, depending on summer soil wetness. In summer, the longer road networks that try to avoid the wet area and the building of corduroy roads across peatland sites are the costlier additions to non-frozen roading costs. The long sections of corduroy roads, also consume a significant part of the wood basket of a harvest unit. Therefore, if a harvest unit is far from a permanent road or if a harvest unit is relatively small it may never be logged in summer due to the high costs. Forestry firms will need to assess the full range of ideas on how to adapt to a shortened period of frozen soil conditions, including more permanent roads, cost sharing, and hauling to satellite yards during the shorter winter.

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Chapter 4: Duration of frozen highway conditions and highway hauling costs of logging operations in future climate scenarios

4.1. Abstract

In this chapter, I developed an empirical statistical temperature prediction model to predict frost depth and the number of days of winter weight premium (WWP) based upon four years of air temperature and road-bed data from three locations in Alberta. The model predicts daily road-bed temperatures at various depths between 15 cm and 80 cm with multiple climate variables; these included minimum, maximum and average daily air temperature, freezing degree days and thawing degree days. The objectives were: 1) to predict future winter weight premium length and 2) to analyze the cost of trucking based upon shortened WWP season at three greenhouse gas radiative forcing values of 2.6, 4.5 and 8.5 for three time intervals (2020 – 2039, 2040 – 2059 and 2070 – 2089). WWP period was projected to decrease by up to 5 days in 2020 – 2039, 13 days for 2040 – 2059 and 32 days for 2070 – 2089and on warmest winter of each period another 12 to 26 days of WWP were lost. The trucking costs due to shorter WWP period during the extreme warm winter was predicted to increase by up to 2% in 2020 – 2039, 6% in 2040 – 2059 and 8% in 2070 – 2089when wood hauled directly to the mill. With the satellite yard use, the trucking costs will increase by up to 5% in 2020 – 2039, 8% in 2040 – 2059 and 16% in 2070 – 2089.

4.2. Introduction

Some regions in North America take advantage of frozen ground conditions to increase the gross vehicle weight (GVW) of transport vehicles on public highways when the subgrade under the asphalt pavement is frozen to a sufficient depth. The increased GVW does not damage highways because frozen water in the subgrade increases the highway road bearing capacity by creating a strong bond between particles and increasing the stiffness of the soil (Johnson et al., 1986; Bigl & Berg, 1996; Asefzadeh et al., 2017; Lachance-Tremblay et al., 2017; Bilodeau et al., 2019). The WWP results in significant savings in the log transport costs for forest companies in northern environments because of transport trucks can carry heavier loads with fewer trips from the harvest areas to the mill site. For example, Bradley and Thiam (2018) estimated that each week of WWP saves the forest industry in Alberta $1.63 million in hauling costs. On the contrary, during breakup or the spring thaw, the GVW is restricted because highways are particularly vulnerable to damage due to excess soil water caused by the melted ice. Thus, the profitability of forest companies is impacted by the weather patterns in fall, winter and spring, and system of winter weight allowance is vulnerable to warming climate. Warmer winter patterns have already been observed in the current climate data (Alberta Agriculture and Forestry, 2019; Kienzle, n.d.) and predictions consistently show continued warmer winters for North America (Johnston et al., 2008; Price et al., 2011; Thornton et al., 2012; Vincent et al., 2012; Wang et al., 2016). Forest managers are already applying some strategies to cope with effects of warming winters such as building more permanent roads, providing more machines and labour, more satellite yards and more summer harvesting (Lemmen et al., 2008; Williamson, et al., 2009; Kuloglu et al., 2019).

Each jurisdiction (province, state, municipality, etc.) is responsible for implementing measures to protect the public highway infrastructure and determines the time of winter weight start and end using one of three methods; 1) frost depth measurements, 2) cumulative freezing/thaw index, or 3) fixed dates (Bradley 2013; Bilodeau et al. 2017). The Alberta provincial government uses the frost depth measurement method. In response to research on haul vehicle configuration and frost depth (Bradley & Thiam, 2018), Alberta changed the way that WWPs are implemented for northern highways in 2017. Now, where bridge infrastructure can support the trucks, Alberta has the highest GVW, 88,000 kg, for on-highway log haul trucks in all of Canada (Bradley & Thiam, 2018). These are huge loads that can do extensive and costly damage to the public road infrastructure if operated when the subgrade is unstable. These highways are the main arteries that connect the harvest areas to the mills. WWPs are implemented on the individual highways when estimated temperature at a depth of 75 cm is 0 °C or below based on the study by Bradley and Thiam (2018). WWPs are removed when the temperature at a depth of 25 cm is above 0 °C (Bilodeau & Dore, 2017). During the spring and mid-winter-thaw season and when WWPs are removed, maximum vehicle weight will be restricted (Alberta Transportation, 2018).

In this paper, we used the data on rate of fall freeze-down and spring thaw of road-beds to explore the relationship between subgrade frost and weather data (Crevier & Delage, 2001; Diefenderfer et al., 2003; Baiz et al., 2008; Asefzadeh et al., 2016). The resulting models were then combined with Global Circulation model (GCM) outputs to explore the effect of climate change predictions on the length of winter weight premium. Thus my objectives were: 1) to predict future WWP period (start and end days) for three location in Alberta; and 2) to assess Alberta future hauling cost on the highway in relation to the length of future WWP in Alberta under the two scenarios- first when all the wood was hauled directly to the mill and second when a portion of the winter harvest volume was hauled to a satellite yard and then the mill yard in summer.

4.3. Methods

4.3.1. Soil and Air Temperature Data

Road-bed soil and air temperature measurements were provided by Alberta Transportation for years 2015 – 2019 between the months of November and April from road-bed monitoring sites at Conklin, Slave Lake and Manning. At each monitoring site the soil temperature was measured at 3 hours intervals with thermistors (YSI 44007, Farnell/Newark) installed at depth (5, 15, 30, 45, 60, 80 cm) below the roadside. The thermistors were positioned on thermistor strings; F-30 type for Conklin, and F-38 type for Slave Lake and Manning both manufactured by Lakewood Systems. Air temperature was measured in 3-hour intervals by a temperature sensor (TP2 2m, Lakewood Systems) enclosed in a 7-plate radiation shield (RS3, Hoskin Scientific) that was secured at a height of 1.8 m at the roadside. The frost depth at 25 cm and 75 cm was linearly interpolated for each 3 hour time (15 cm and 30 cm for 25 cm, and 60 cm and 80 cm for 75 cm frost depth).

4.3.2. Prediction of Soil Temperature from Air Temperature

The weather data were used to calculate eight variables for November to April of 2015 – 2019: 1) daily average air temperature, 2) maximum daily air temperature, 3) minimum daily air temperature, 4) average air temperature of previous 3 days, 5) freezing degree days, 6) thawing degree days, 7) solar radiation for three monitoring sites (Alberta Agriculture and Forestry, 2019), and 8) temperature difference from the previous day represents the temperature change. The day length, difference between sunrise and sunset in minutes, was also included in the model (citipedia.com, 2019). Freezing degree days were calculated as cumulative when daily average air temperature drops below 0 °C for freeze up period (from November 1st to January 31st) and thawed period (from January 1st to April 30th) while thawing degree days were sum of the average daily air temperature above 0 °C . Solar radiation was estimated by Hargreaves and Samani (1982, 1985) equation uses interpolated maximum and minimum temperature measurements (Alberta Agriculture and Forestry, 2019). These nine variables were then used to develop soil temperature prediction models at depths of 15 cm, 30 cm, 60 cm and 80 cm with AIC based forward-backward stepwise regression analysis (RStudio Team, 2016). Daily data of 367 days (from November 1st to January 31st, for 2015 to 2019) were used to predict freeze up (soil temperature at the depth of 60 cm and 80cm) for the three locations. We used daily data for about 480 days (from January 1st to April 30th, for 2015 to 2019) for the thawed predictions (soil temperature at the depth of 15 cm and 30 cm) for the three locations. This provided a total of 12 prediction models (four for each of the three monitoring sites) that were cross-analyzed between sites and the model fitness was assessed with the root mean square error (RMSE) and variance explained value. The variables from the best fit regression model was chosen for the climate change analysis at all sites; the regression models for each sites was then refit with these variables to generate models with coefficients.

4.3.3. WWP Start and End Date Selection

Alberta Transportation staff assign the WWP program in the fall when the soil temperature is below 0 °C at depth 75 cm, indicating that the frost depth has reached 75 cm. This was relatively stable in the data records and easy to replicate with our simulations. However, to end the WWP program in the spring, Alberta Transportation staff use a more subjective method. Once a depth of 25 cm has thawed for three days (soil temperature is above 0 °C), a staff member uses the local weather forecast to judge if refreezing is likely in the next three days. If the weather forecast predicted sustained warm conditions, Alberta Transportation end the WWP by issuing a 3-day notice to the trucking industries. To remove the subjectivity and automate the process an Excel macro was programmed to find a seven consecutive days above 0 °C at the depth of 25 cm in between January and March. This approach coincided well with actual end date and predicted end date.

4.3.4. Future Climate

We used Lars –WG 6.0 (Semenov & Barrow, 2018) stochastic downscaling weather generator model for 2020 – 2039, 2040 – 2059 and 2070 – 2089 predictions. The weather generator projects daily maximum and minimum temperatures. We obtained 20 years historical weather data (1995 – 2015) from Daymet (Thornton et al., 2012) for the future predictions. We chose climate model HadGEM2-ES based on previous study (Kuloglu et al., 2019) with the three Representative Concentration Pathways (RCPs), the greenhouse gas radiative forcing values of 2.6, 4.5 and 8.5, for future predictions.

4.3.5. Study Area

To determine the cost of the changing climate to a forest company, we used a hypothetical forest company that was located in Alberta. Around two-third of the total annual allowable cut of Alberta usually was harvested and hauled in the winter season. Thus, it was assumed that the company harvests 750,000 m^3/year in summer and 1,500,000 m^3/year in the winter. Because soil and air temperature measurements were from Conklin, Slave Lake and Manning, we assumed the hypothetical forest was located at a midpoint of these monitoring sites.

4.3.6. Cost Calculator

We used the hauling cost calculator, developed by Kuloglu et al. (2019), for trucking cost calculation (Appendix C.1 and Appendix C.2). The unit cost ($\$/m^3$) of hauling consists of equipment ownership cost, labour cost and operational cost. The ownership includes depreciation, insurance and return on capital. The average speed of loaded hauling trucks was 60 km per hour and unloaded was 90 km per hour. Truck running time considered 21 hours for summer and 19 hours for winter seasons. We only considered the hauling on highway with 10 Axle B-Trains that can carry a load up to 88,000 kg during the WWP period, however, the allowed weights might be limited to 63,500 kg because of the bridge carrying limitation (Alberta Transportation, 2015). Thus, truck load carrying capacity in this study was considered as 75,700 kg (the average of 88,000 kg and 63,500 kg) in winter. The truck load carrying capacity for summer was estimated at 47,300 kg.

Two scenarios were used to determine the potential cost of future hauling. In the first scenario, i.e., trucks hauled all the wood from harvest areas to the mill yard which was assumed to be 250 km away with 8 hours per cycle[1]. In the second scenario, satellite yards were used as storage areas approximately 40 km away from the harvest site with 2 hours of cycle time. Satellite yards provide flexible options during the warmer winter. Satellite yards were used to supply wood to the mill when the shut-down occurs during the winter thaw, break-up season and summer bird nesting season. Satellite yards decrease idle equipment in summer, however, increase costs because of extra unloading/loading cost at the satellite yard location (Kuloglu et al., 2019). The Generalized Reduced Gradient (GRG) algorithm in Excel solver was used to

[1] Cycle time for mill calculated as (250 km/90 km/hr + 250 km/60 km/hr+(30 min loading time+20 min unloading time)/60)
For satellite yard: (40 km/90 km/hr + 40 km/60 km/hr+(30 min loading time+20 min unloading time)60)

minimize the number of idle trucks year-round by partitioning the amount of wood between the mill and the satellite yard in winter and then using the summer hauling season to haul the wood from the satellite yard to the mill.

4.4. Results

4.4.1. Soil Temperature Prediction Models

We developed site specific prediction model and cross analyzed each model at all three sites. We compared RSME values of site-specific model and models for other sites (Table 4.1, Appendix C.3). From this we selected a standard set of parameters model for each site based on the model developed for Conklin sites (Eq. 1 – 4). For example, RMSE value of model developed originally for Manning was 1.322 for soil temperature predictions at the depth of 80 cm. RMSE value of model developed for Manning with Conklin parameters was 1.324 for 80 cm soil temperature. As a comparison, the RMSE value of model developed for Manning with Slave Lake parameters was 2.311 for 80 cm. We also plotted cumulative percentage of variance explained in order to show how much of the variance was explained among the models (Table 4.2, Appendix C.4).

Table 4.1 RMSE values of models developed with Conklin parameters for each monitoring sites

RSME values of final regression models (Conklin-like Model)[1]			
	Conklin	Slave Lake	Manning
15 cm	2.178	1.844	1.962
30 cm	2.257	1.849	1.761
60 cm	1.496	1.484	1.416
80 cm	1.464	1.406	1.324

[1.] RMSE values of site specific models are in Appendix C.3

Table 4.2 Cumulative percentage of variance explained by the 12 regression models

Percent of variance explained by the final regression models (Conklin-like Model)			
	Conklin	Slave Lake	Manning
15 cm	92.3	94.7	95.1
30 cm	90.9	94.1	95.1
60 cm	88.3	87.2	89.4
80 cm	86.4	85.9	88.8

The variables listed in Eq. 1 – 4 were then used to develop regressions for each monitoring site (Appendix C.5: Coefficients of variables).

$$Tp_{15} = a_{15} + b_{15}A_p + c_{15}F_{dd} + d_{15}T_{dd} + e_{15}T_{min} \quad \text{Eq. 1}$$

$$Tp_{30} = a_{30} + b_{30}A_p + c_{30}F_{dd} + d_{30}T_{dd} + e_{30}T_{min} \quad \text{Eq. 2}$$

$$Tp_{60} = a_{60} + b_{60}A_p + c_{60}F_{dd} + d_{60}T_{dd} + e_{60}T_{min} + f_{60}T_{ave} \quad \text{Eq. 3}$$

$$Tp_{80} = a_{80} + b_{80}A_p + c_{80}F_{dd} + d_{80}T_{dd} + e_{80}T_{min} + f_{80}T_{ave} \quad \text{Eq. 4}$$

where;

Tp_{15}: predicted soil/pavement temperature at 15 cm depth (°C),

Tp_{30}: predicted soil/pavement temperature at 30 cm depth (°C),

Tp_{60} : predicted soil/pavement temperature at 60 cm depth (°C),

Tp_{80} : predicted soil/pavement temperature at 80 cm depth (°C),

a_i : intercept coefficient for prediction of depth temperature i (15, 30, 60 and 80 cm),

b_i : three-day average temperature coefficient for prediction of depth temperature i,

A_p : three-day average temperature

c_i : freezing degree days coefficient for prediction of depth temperature i,

F_{dd} : freezing degree days

d_i : thawing degree days coefficient for prediction of depth temperature i,

T_{dd} : thawing degree days

e_i : minimum daily air temperature coefficient for prediction of depth temperature i,

T_{min} : minimum daily air temperature

f_i : average daily air temperature coefficient for prediction of depth temperature i,

T_{ave} : average daily air temperature

4.4.2. Days of Winter Weight Premium

We calculated WWP length of three monitoring sites for 2015 – 2019 using the winter weight start and end criteria. WWP ranges between 120 days and 160 days during the observed 4 years period (Table 4.3). We used the average of these 4-year data as a base case in order to compare future changes. The observed (actual) and predicted WWP dates, model slightly underestimated the start date and overestimated the WWP end date (**Error! Reference source not found.**).

Table 4.3 Predicted days of winter weight premium on three monitoring sites for 2015 – 2019.

Year/Location	Conklin	Slave Lake	Manning
2015-2016	128	123	130
2016-2017	120	120	125
2017-2018	159	160	158
2018-2019	130	128	132
Average (Base Case)	134.2	132.7	136.2

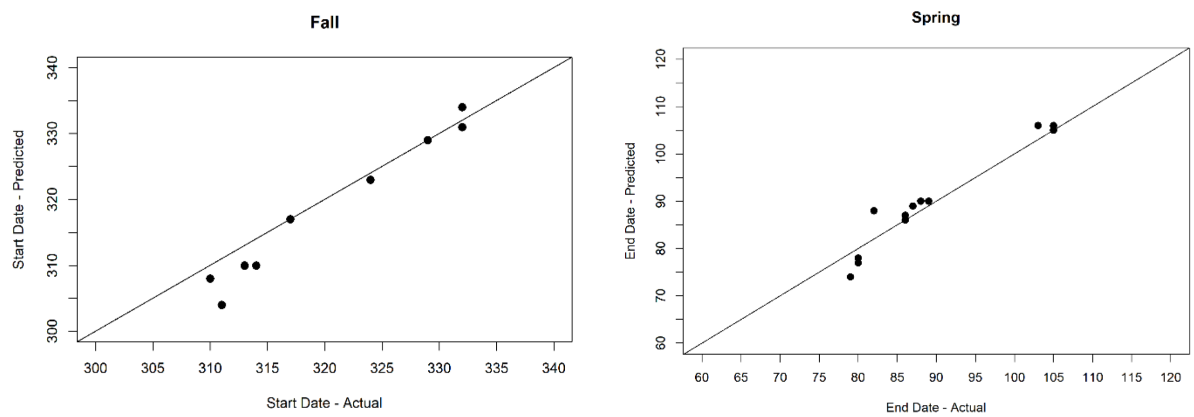

Figure 4.1 WWP start date predicted and start date actual in fall (left) b. WWP end date predicted and end date actual in spring (right)

Average WWP days for three monitoring sites between 2020 and 2039 were estimated to be 134 days under the climate scenario of RCP 2.6, 132 days for RCP 4.5 scenario and 130 days for RCP 8.5. Winter weight premium in 2040 – 2059 were expected to be 132 days with RCP 2.6, 126 days with RCP 4.5 and 123 days with RCP 8.5. In the 2070 – 2089, WWP were estimated to be 125 days under the scenarios of RCP 2.6, 121 days under RCP 4.5, and 107 days for RCP 8.5 (Table 4.4). In the extreme warm winter year, WWP decreases to 83 days in 2070 – 2089.

Table 4.4 Average projected Winter Weight Premium for the HadGEM2-ES Model with three time intervals and three radiative forcing values (RCP) from three monitoring sites and base case scenario (Table 4.3). The year with shortest period of WWP was reported for each interval.

Time Intervals	Scenario	Conklin	Slave Lake	Manning
2015 – 2019	Base Case	134	132.7	136.2
2020 – 2039	RCP 2.6	133.3	132.8	136.1
	RCP 4.5	131.7	130.4	134.1
	RCP 8.5	129.8	128.6	133.6
	EXT. Year[1]	110	112	125
2040 – 2059	RCP 2.6	130.8	130.7	135.2
	RCP 4.5	126.2	121.9	129.8
	RCP 8.5	122.8	120.1	125.9
	EXT. Year[1]	103	108	109
2070 – 2089	RCP 2.6	126.7	122.1	128.4
	RCP 4.5	119.7	117.1	125.5
	RCP 8.5	109.8	100.2	110.4
	EXT. Year[1]	85	83	84

[1] The extreme year (EXT. Year) had the warmest winter in any of the RCP values of a time interval

4.4.3. Estimated Hauling Cost

The summer logging season included 153 days for calculate hauling. In total there are a gross of 214 days, less 61 days for break-up (historically in April). Summer logging days were held constant for cost calculation of future scenarios.

4.4.3.1. Hauling Directly to Mill

The annual hauling cost estimated for 2015 – 2019 logging seasons was $14,074,000 when WWP was 160 days (Table 4.3); $14,669,000 when WWP was 120 days. The average WWP days (134 days) for 2015 – 2019 seasons, the hauling cost was estimated to be $14,459,000. Using the hauling cost calculator and WWP days in Table 4.4, the future hauling costs were estimated for a hypothetical forest company located midpoint of three monitoring sites and three time intervals with three radiative forcing values (Table 4.5).

Table 4.5 Total cost of the hauling (winter and summer) directly to the mill only ($ thousands) for three time intervals and 3 radiative forcing values and base case scenario (Table 4.3)

Time Intervals	Scenarios	Conklin	Slave Lake	Manning
2015 – 2019	Base Case	$14,459	$14,467	$14,383
2020 – 2039	RCP 2.6	$14,464	$14,487	$14,384
	RCP 4.5	$14,473	$14,480	$14,460
	RCP 8.5	$14,483	$14,489	$14,463
	EXT. Year	$14,860	$14,848	$14,575
2040 – 2059	RCP 2.6	$14,477	$14,478	$14,454
	RCP 4.5	$14,568	$14,658	$14,483
	RCP 8.5	$14,587	$14,668	$14,570
	EXT. Year	$15,037	$15,873	$14,867
2070 – 2089	RCP 2.6	$14,565	$14,657	$14,490
	RCP 4.5	$14,671	$14,686	$14,572
	RCP 8.5	$14,862	$15,055	$14,858
	EXT. Year	$15,493	$15,574	$15,501

One week loss on WWP (from 134 days to 127 days) increased the costs of hauling by $105,000 and required an additional hauling truck to finish the haul in time. This increased the idle haul trucks in summer from 8 to 9 trucks. When there was a one month loss on WWP (from 134 days to 104 days), total hauling cost rose by $506,000. In order to make up the one month loss, an extra 5 trucks were needed resulting 13 idle trucks in summer. The forest company needed an additional 12 trucks for a total increase in hauling cost of $1,116,000 in the event of an extremely warm winter (83 days of WWP).

4.4.3.2. Hauling to Mill and Satellite Yard

To minimize number of idle equipment when WWP was 160 days, 1,273,000 m^3 needed to be hauled directly to the mill and the remainder 127,000 m^3 stored in satellite yard. The annual hauling cost estimated for 2015 – 2019 logging seasons was $15,653,000 when WWP was 160 days (Table 4.3); $16,747,000 when WWP was 120 days when the forest company haul some of the wood to mill (1,152,000 m^3) and satellite yard (248,000 m^3) in winter season. In this scenario, the forest company was required to unload at the satellite yard and reload in summer. The cost of hauling increased by $469,000 because of additional unloading/loading when WWP was 160 days; and by $947,000 when WWP was 120 days (Table 4.6).

The annual hauling and unloading/loading cost estimated to be $17,127,000 when the WWP was 134 days. A one week loss on WWP (from 134 days to 127 days) increased the costs of hauling and unloading/loading by $372,000 and 1 additional truck was needed. When there was a one month loss on WWP (from 134 days to 104 days), this cost rose by $1,657,000 and 2 additional trucks were needed. In the event of an extreme warm winter (83 days of WWP), the cost increased by $2,857,000 compared to 134 days of WWP and 3 additional trucks were needed.

Table 4.6 Cost of hauling directly to the mill and some from satellite yard ($ thousands) - minimize idle equipment in the summer/year around + unloading/loading cost in the satellite yard for three time intervals, for 3 radiative forcing values and base case scenario (Table 4.3).

Time Intervals	Scenarios	Conklin	Slave Lake	Manning
2015 – 2019	Base Case	$17,197	$17,318	$17,059
2020 – 2039	RCP 2.6	$17,291	$17,315	$17,127
	RCP 4.5	$17,359	$17,415	$17,201
	RCP 8.5	$17,427	$17,472	$17,215
	EXT. Year	$18,215	$18,155	$17,594
2040 – 2059	RCP 2.6	$17,408	$17,410	$17,141
	RCP 4.5	$17,522	$17,675	$17,427
	RCP 8.5	$17,611	$17,690	$17,562
	EXT. Year	$18,848	$18,350	$18,265
2070 – 2089	RCP 2.6	$17,519	$17,629	$17,479
	RCP 4.5	$17,705	$17,847	$17,588
	RCP 8.5	$18,236	$19,155	$18,200
	EXT. Year	$19,900	$19,984	$19,913

4.5. Discussion

4.5.1. Climate Change Impacts to Winter Weight Premium Program

This study showed that WWP length will decrease by more than two weeks to an average of 110 days for Conklin, 100 days for Slave Lake and 110 days for Manning in the average year of RCP 8.5 in the 2070 – 2089. In the extremely warm winter of the 2070 – 2089period, WWP could decline to 83 days. Hauling cost, already one of the highest cost components of the wood supply (Pan et al., 2008; Kuloglu et al., 2019) would go up (by between $105,000 and $2,857,000). In addition to the analyzed impacts to the forest company hauling costs, the shorter WWP may cause other issues. For example, the supply chain may be affected because the reduced ability to haul wood volume directly to the mill. Moreover, increased truck traffic during the summer or spring weight can affect the pavement life and increases cost of repair and maintenance (Bai et al., 2010). Increasing warming winter trends resulting in declined WWP days will economically impact forestry and the trucking industry.

In addition to the shortening of the program, the frost depth, especially at 25 cm in the spring / late winter months will likely be less stable in future. Figure 4.2 shows and example of such instability with the model prediction of Conklin 25 cm soil temperature and daily temperature range in the late winter of 2089. This may cause the WWP to be more complex because of the certain and shifting weather of late winter. In the example in Figure 4.2, the algorithm presented here terminated the WWP on February 24th even though there were sporadic periods of re-freezing well into March. Thawing increases the water content in the pavement which softens the structure and increases the road susceptibility to damage; such as pavement rutting (Erlingson, 2010). However, the thaw and freeze cycle can increase the potential for structural damage to pavement even without heavy traffic (Lemmen et al., 2008). The refreezing of subgrades with increased moisture can lead to increased potholes, cracking, frost heaving raise, road deflection and rutting. Badiane et al. (2015) reported damage even after one freeze-thaw cycle so the possible impact on pavement and resulting truck weight restriction during a freeze and thaw cycle shown in Figure 4.2 is hard to determine. However, this is likely the WWP will be more restrictive than current policies and the thaw-freezing cycle will likely induce more costly damage to public infrastructure.

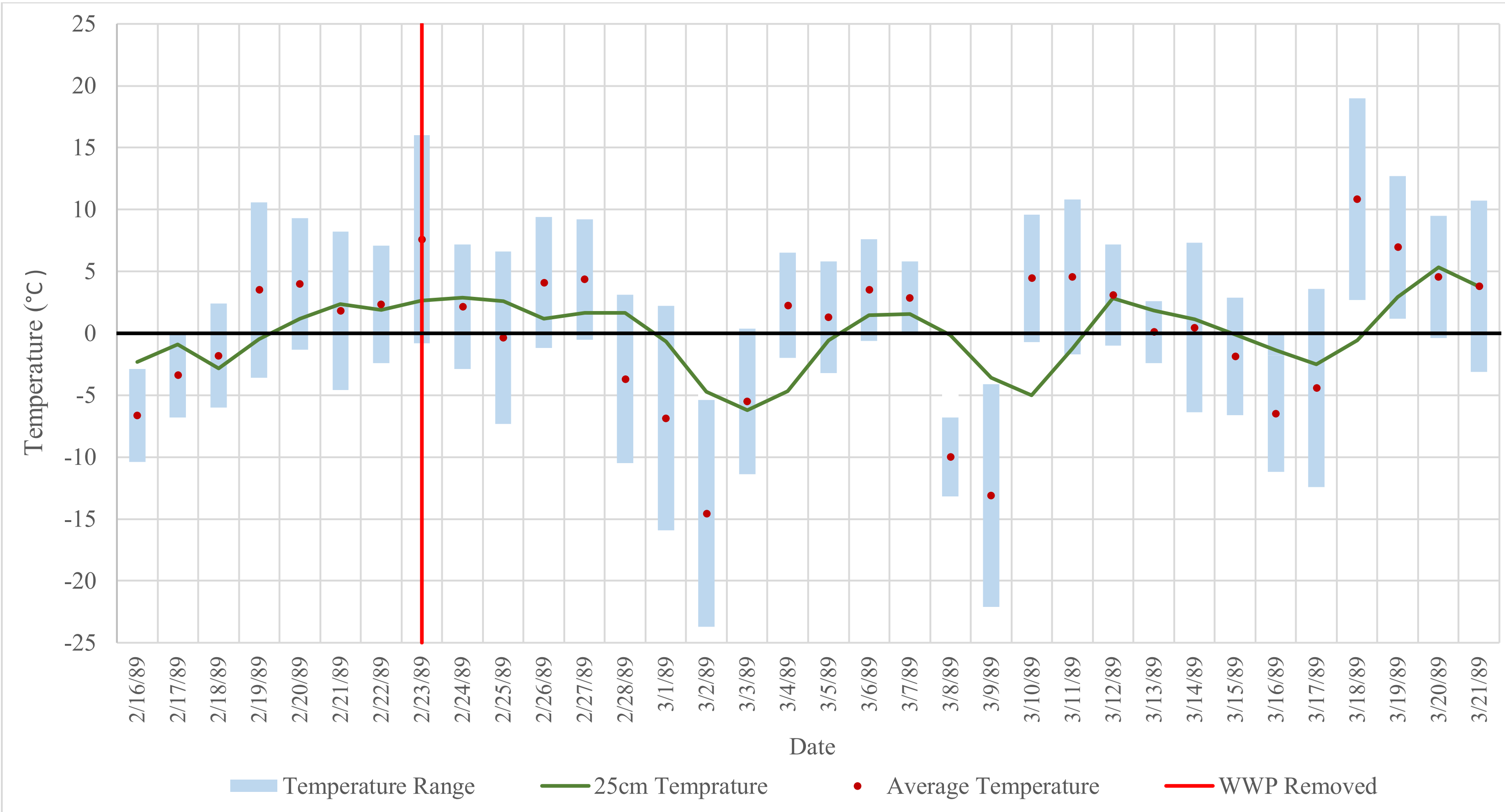

Figure 4.2 Modelled prediction of soil temperature at 25 cm and daily air temperature range in the 2089 with WWP removal date

4.5.2. Cost/Number of Trucks Increase

This study shows that the cost of hauling directly to the mill increases when WWP length decreases. We estimated the hauling cost will increase by $105,000 for 1 week loss, $506,000 for 1 month loss and $1,116,000 for the extreme warm winter (83 days of WWP) in 2070 – 2089. Much of this was related to the need to buy extra trucks and account for more idle time of these trucks in the summer period. In order to minimize idle equipment during the summer, the forest company can use the satellite yard and haul in summer. The satellite yard, however, increases the summer hauling cost due to smaller loads and additional unloading and loading at the satellite yard location. In the event of satellite yard use and WWP loss of 1 week, hauling and unloading/loading cost would increase by $327,000, $1,657,000 for 1 month loss and $2,857,000 for extreme warm winter (83 days of WWP) in 2070 – 2089. Estimated hauling costs in this study were in the same range reported by Brandley and Thiam (2018). We should note, however, that use of satellite yards offers the firm more flexibility and is better for the continuity of work for the trucking fleet.

We expect that the increase in cost of direct haul to the mill might be slightly underestimated as direct haul requires daily access to the logging site. Kuloglu et al. (2019) show that surface thawing of logging access roads during some mid-winter days will result in additional shut-down days for trucks expecting to load at the logging site and haul directly to the mill. Brief thawing conditions above 6 °C (maximum daily air temperature) in winter months would mean shut-down of direct haul – except perhaps with night loading. This will be a further reason for satellite yards as trucks could be loaded at satellite yard during these brief warm periods in winter and hauled to the mill in these short periods of thaw.

4.5.3. Prediction Models

The prediction models to estimate WWP start and end dates, produced satisfactory results in this study because winter weather data separated into two dataset; freeze up (from November 1st to January 31st) and thaw (from January 1st to April 30th). One of the objectives of this study to create a generic model to predict WWP start and end dates. We cross-analyzed and compared the RSME values of the site specific model and generic model. Moreover, the results showed that there was little bias between the predicted and actual dates.

Other models in order to predict WWP start and end dates use a different approach such as cumulative thawing index and cumulative freezing index (Doré, 2004; Bradley et al., 2012; Asefzades et al., 2016). Furthermore, our prediction model had different variables than those previously used (Diefendenfer et al., 2003; Asefzades et al., 2017) to predict asphalt temperature with daily average air temperature and daily solar radiation. Solar radiation was found statistically not significant based on AIC forward-backward stepwise regression analysis used in this study. Due to the solar radiation angle during the winter season in northern Alberta, it had low impact on our prediction models.

4.5.4. Other Strategies

Other strategies to deal with cost increases associated with shorter WWP length that forest companies can adopt are harvesting more in summer time with lighter truck loads and investing on more satellite yards and truck inventory as well as more permanent roads. Technologically advanced trucks that decreases pressure and distribute weight evenly on the asphalt pavement. Forest companies already using central tire inflation (CTI) system that allows trucks to deflate their tires, provide larger tracks that decreases environmental damage, maintenance costs and fuel consumption while increasing tire life.

4.6. Conclusion

The number of Winter Weight Premium days were projected to decrease by up to 32 days in the 2070 – 2089 with the RCP 8.5 forcing value. The shorter WWP might lead a forestry firms to provide more hauling trucks resulting in hauling cost increase 8% greater than the base case scenario if wood is hauled directly to the mill and 16% greater if wood is hauled to mill and satellite yard. Thawed conditions will also impact in-block hauling, thus using satellite yards will provide flexibility and continuity for forest operations.

4.7. References

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Chapter 5: Discussion and Conclusion

Climate change is expected to affect the length and severity of winters in the North America. To cope with shorter more variable winters, forest companies can use strategies such as employing more seasonal labour and equipment in the winter, using satellite wood storage yards close to harvest areas, and harvesting more in the summer season. This study analyzed how the shorter periods of frozen ground may impact the costs of forest operations in Alberta and cooler parts of North America. The economic effects of adaptation strategies, such as using more machines and labour, satellite yard and switching harvesting season were analyzed here to determine the possible impact on forest companies.

The climate model estimated that there is an increased warming trend especially in winter (Wang et al., 2016, Thornton et al., 2012, Johnston et al., 2008; Price et al., 2011; Vincent et al., 2012). The mean temperature in Alberta increased by 5.5 °C between 1950 and 2010 (Kienzle, n.d.) and it is predicted that the average winter temperature will increase a further 8 °C by 2070 – 2089 (Wang et al., 2016; Semenov & Barrow, 2002; Thornton et al., 2012). This winter warming trend reduces the period of frozen soil conditions resulting in declined access for harvesting sites and eligible days for logging operations (Spittlehouse & Stewart, 2003). Moreover, warmer and shorter winters due to climate change will potentially limit access crossing wetlands (Spittlehouse & Stewart, 2003), increase delivered wood costs (Sauchyn et al, 2009; Williamson et al., 2009), increase soil disturbance of forest and peatland (Aust & Blinn, 2004) and affect regeneration (Frey et al., 2003). Up to 50% of forest management agreement area might be lost due to a continued warming trend that reduce accessing and crossing wetlands in boreal forest (ICF Marbek, 2012).

5.1. The Change in the Winter Season

The projected shut-down days for in-block hauling were estimated to be between 31 to 48 days by 2070 – 2089 compared to base case scenario (12 days) and between 23 and 36 days for harvesting (9 days shut-down on the base case scenario). Rittenhouse and Rissman (2015) study showed similar shortening pattern which was 2 to 3 week reduction of frozen ground from 1948 to 2012. We also evaluated shut-downs for each month during the winter logging season. For example, March is most likely to be lost as a useful month for winter logging by the 2070 – 2089and companies would likely not plan for frozen conditions during this time if the 6 °C maximum air temperature was used as the threshold for shut-down. On the other hand, November is predicted to remain more stably cool in the future. This likely relates to the short period of daylight and low solar angle in November, which is nearer to the winter solstice than the month of March.

This study showed that WWP length will decrease by more than two weeks to between 100 days and 110 days in northern Alberta in the average year of RCP 8.5 in the 2070 – 2089. An analysis by National Round Table on the Environment & the Economy (2011) showed that timber quantities could decrease by between 9% and 14% in Alberta as climate change increases overtime. The shorter WWP may hinder wood supply if it means that logging access was shifted to summer and some of the cutting areas were then too expensive to access.

5.2. Impact on Cost

5.2.1. Cost of Logging

Spittlehouse and Stewart (2003) suggested developing alternate harvesting system and implementing alternate harvesting practices to deal with shorter and warmer winter season. In order to provide consistent wood supply to the mill, we analyzed two scenarios where the harvested wood was hauled only to the mill yard and some part of the wood was hauled to a satellite yard. Thees (2013) suggested, similar to my research, increasing equipment and work hours/day to cope with a shorter harvesting period. If forest companies employ more seasonal labour and more equipment used only in the winter, the cost of forest operations were expected to increase by 5 % to 11% by 2070 – 2089. This strategy resulted in more idle equipment in summer because wood volume harvested in the summer season is usually about half of that in the winter season. In the warmest winter of the 2070 – 2089, equipment needs would be more than double; the idle machines increased to 243 during the extremely warm year in 2070 – 2089when wood hauled directly to the mill compared to 90 days in 2015 – 2016 logging season. Idle machines increased from 62 to 139 when wood hauled satellite yard to decrease idle hauling truck.

Use of satellite yards distributes winter harvest volume to mill and yard in order to minimize the total number of idle trucks. However, satellite yards increased the total logging costs by 6% because unloading/loading at the satellite yard is required and load capacity of haul truck in summer is lower. Satellite yards, however, give feasible solutions to uncertain extreme weather changes, so companies can plan logging operations on a year to year basis. Satellite yards also allow deliveries to the mill during the break-up season (restricted to spring seasonal weight), the nesting times of birds, and wet periods in summer. Furthermore, the trucking fleet has nearly full-time employment with use of satellite yards and this stability in employment will likely result in a more skilled and efficient hauling trucking workforce. Forest companies are already using satellite yards to manage increased weather shut-down during the winter, and longer distances between harvest areas and the mill.

5.2.2. Cost of Road Construction

Another adaption to a shorter winter logging season addressed in this thesis was switching logging activities from frozen to non-frozen conditions. This will increase average cost of temporary access and in-block road construction, in the wetland-rich landscape of northern Alberta, from \$1,200 per km to \$5,962 per km in thawed conditions. Furthermore, the average cost per m^3 of building temporary roading into cutblocks went from 0.30 $\$/m^3$ in winter to 2.14 $\$/m^3$ in summer. The increase in summer road construction came from several sources: the need for stump removal, roll back of organic layer on mineral soil areas, soil decompaction/road restoration, or bridges to cross streams – all of which have much more economical solutions in frozen conditions. Also, the winter road network is shorter because roads can be located directly across wetlands. One of the largest cost increases, in non-frozen conditions, however, comes from the requirement to construct large amounts of corduroy roads to cross wet mineral soil sites and peatlands in summer. Moreover, large amounts of wood could be consumed in corduroy roads that would reduce the size of the wood basket available for the mill.

The cost of non-frozen temporary roads might be reduced if longer skid distances accompanied a decrease in in-block road density. However, increased skidder traffic can damage wet soils or use of longer skidding might simply transfer the roading cost to the skidding operations. It is likely that some cutblocks that can be accessed only across extensive wetland areas would be viewed as unsuitable for summer logging in most planning systems. This is especially true if the wood basket in the area available for logging is small, therefore the unit cost of road building in $\$/m^3$ would be very high.

5.2.3. Hauling

Truck carrying capacity allowed on highways is increase during the winter season as the frozen pavement can support heavier loads without damage. Warmer winters will increase thawing events resulting in vulnerable pavement structure. Bradley and Thiam (2018) estimated that each week of winter weight premiums (WWP) saves the forest industry in Alberta $1.63 million in hauling costs. Hauling costs would go up in relation to the shorter WWP period because forest companies might need to provide additional hauling trucks and drivers. The hauling costs of my theoretical forestry firm, when all of the wood haul to the mill directly, were estimated to increase by $105,000 for 1 week loss, $506,000 for 1 month loss and $1,116,000 in the event of an extremely warm winter (51 days loss).

If a satellite yard were used and the loss of one week of WWP would increase hauling and unloading/loading costs by $327,000, and $1,657,000 for 1 month loss of WWP. It is expected that my estimated costs of hauling directly to the mill was slightly underestimated as direct haul would require daily access to the logging sites. Direct hauling would have had additional shut-down days as trucks would have been off-limits to cutblocks during brief periods of mid-winter thaw. The wood already stored in satellite yards would be available to be hauled to the mill during these brief periods of mid-winter thaw.

5.3. Other Strategies

During warm mid-winter days, operations might be concentrated to night operation when soil might refreeze to allow support of machine traffic. There is a possibility that logging technologies in future may reduce or eliminate the soil damage that equipment and hauling trucks cause (MacDonald, 1999). Specialized equipment with wider and low-pressure tires with high flotation, or covering logging and skidding trails with logging slash or wood chips might allow support of machine weight thereby limiting soil disturbance. Forest companies already using central tire inflation (CTI) system that allows trucks to deflate their tires. The reduced tire pressure increases the tire footprint on the temporary roads resulting better flotation and less rutting compared to tires with high pressure. Thees (2013) suggested changing harvesting method to cable based system to mitigate soil disturbance. However, cable logging systems are not well suited for flat terrain such as north and central Alberta.

Better road construction techniques that seal the surface, shed moisture and have structures such as specialized culvert and bridges can be used to eliminate the need for seasonal weight restriction during the thaw season (Spittlehouse, 2005; McGregor et al., 2008; Gauthier et al., 2014); we expect such upgrades to road structures to be costly. Moreover, building more permanent roads would help with accessibility to harvest areas (Johnston et al., 2010). In some cases, however, cost of access roads can be shared with other resource sectors. Shared permanent road construction associated with the energy and forestry sectors (Schneider et al., 2003; Alberta Pacific Industries, 2018) could decrease the amount of temporary road needed and provide more opportunity for possible transitional cutblocks that are suitable for both winter and summer operations. However, these types of all-weather roads are expensive to build, and some governments limit the number of permanent roads to protect other values of forest lands.

The climate model HadGEM2-ES was selected from the climate models available (EC-EARTH, GFDL-CM3, HadGEM2-ES, MIROC5, MPI-ESM-MR) because HadGEM2-ES covers all of the scenarios that we planned, including a RCP 2.6 scenario, absent from most of other models. Moreover, Sheffield et al. (2013a, 2013b) showed that HadGEM2-ES received a higher pattern correlation coefficient, and lower bias and errors than the other models.

Regression models were used to estimate soil temperate and frost at 75 cm and 25 cm depth in order to determine start and end of the WWP period. My models produced satisfactory results and there was little bias between the predicted and actual dates.

5.4. Conclusions

Climate models predict shorter winters with more periods of mid-winter thaw in the future. The economic viability of forestry companies in much of the Canadian boreal forest is dependent upon accessibility of logging sites over frozen substrates. Shorter winters with periods of mid-winter thaw will influence which areas will be harvest in winter, the economic feasibility of logging small cutblocks accessible only across winter (frozen) road and the use of various mitigation measures such as use of satellite log storage yards, more machines, shifting to summer logging operations with adaption to machines to limit damage to substrates.

The gradual increase in operation costs due to warmer winter and shorter periods of frozen ground will impact harvesting practices. These collective adaption options analyzed here will economically challenge forest companies if market price for wood do not increase as the costs of delivered wood increase.

5.5. Recommendations for Future Research

5.5.1. Landscape Level Considerations

The transitioning to summer logging needs to be investigated further. Timber supply analysis will be necessary to help forest companies to eliminate the areas that are not accessible or too expensive to access during the summer logging. Moreover, forest companies might require new harvesting areas based on timber availability in changing climate. Forecasting the timber availability in the close distance areas with timber supply analysis can decrease the roading costs especially extremely wet logging sites that required a high amount of corduroy roads installation. However, this might lead to cutting heavily from more accessible areas, leaving remote and isolated areas unharvested. Aggregated harvesting can help to provide timber supply to the mill when further areas won't be accessible in the future. The adjacent cutblocks can be a source of timber thus, increased roading costs for longer distances and soil damage from summer harvest can be prevented.

Decompaction cost was calculated for the access and in-block roading in this study. Increased summer logging areas will potentially increase soil damage and rutting not only on access and in-block roads but also on the harvesting site as well, thus decompaction and planting of the harvesting site should be included in the logging cost calculation as well. Satellite yard usage might be integrated into the summer logging as well. If forest companies haul to satellite yards, which are close to harvesting sites, in summer and haul to mill in winter to take advantage of WWP and with heavier loads.

Landscape configuration in terms of wetland distribution might change in the future depending on precipitation and temperature increases. The loss of wetlands might create more summer harvesting sites. In order to determine summer and winter harvesting sites, future wetland distribution also need to be assessed.

5.5.2. Operational Level Considerations

Corduroy alternatives to cross wetlands can be analyzed to determine their economic effectiveness. Brush mats (or slash mats consists of branches and top trees) can be cheaper options to increase road bearing capacity, however, leaves may become loose and block water passage. (Arnold & Gaddum, 1995; Partington et al., 2006). Moreover, the depth of the brush mats needs to be higher than corduroy logs which increases costs. Also, additional labour is needed to collect the top residuals resulting in cost increases (Gerasimov et al., 2007). Rig mats (access mats) and timber bridges, made of wood and steel, are modular, reusable, and rentable, however, there are additional transportation costs. An aggregated mattress can be used for surface and subsurface flow, but removing is difficult and they might sink similar to rubberized mats (Partington et al., 2006).

Alternative ways to deliver wood to the satellite yard can also be explored. The smaller, cheaper, and more off-highway suitable trucks can deliver wood for a short distance from logging sites to storage yards. This will allow the construction of lower standard off-highway roads in summer and winter, as well as decrease damaging temporary roads.

The cost and benefit analysis of permanent road development needs to be analyzed in future studies to determine the value of the establishment. Permanent road development can be assessed based on the overall benefits to forestry and other resource sectors, as well as local communities. Besides the monetary values, how permanent roads affect the other values of forest land (such as disturbing soil and habitat) also needs to be evaluated.

5.5.3. Cumulative Costs of Shorter Winter

To understand the whole economic impact of the shorter winter season on forest operations, these adaption strategies need to be analyzed all together. An economic analysis for a contingency plan during the extremely warm winter is necessary in order to adapt these strategies to minimize the costs and reduce the economic burden to a forest company. A decision-making tool can be developed to analyze the economic costliness of the collective adaption options analyzed in this study. The heuristic model can be used to minimize logging costs to deal with shorter winter with different adaption options as constraints. The model can allocate adaption options while limiting the number of equipment, adjusting the volume of timber that goes to mill and/or satellite yard, determining harvesting season based on roading cost, and increasing/decreasing hauled weight based on length of WWP in the future. Decision-making tool (heuristic algorithms) with sensitivity analysis can help to assess how timber supply might be affected by uncertain climate such as warming winter temperatures. Further, variation in soil wetness to access during summer could also be considered. Predictor variables such as period of frozen ground, cutblock size (aggregated harvesting units), distance to permanent roads, mill, and satellite yard can be used for the sensitivity analysis to show the influence of each variable on logging costs. Sensitivity analysis can also be applied to assess the effect of the variables on accessing timber supply. Variables such as uncertain winter temperatures and logging costs might be used for sensitivity analysis that will assist forest companies to determine timber supply for future operations.

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Appendices

Appendix A Spreadsheet model – Logging cost calculator

Appendix A.1 Summary – Result Panel

	A	B		C	
1		Base Year		Future Predictions	
2		Summer	Winter	Summer	Winter
3	Hours/Day	21	19	21	19
4	Total Days	214	151	214	151
5	Breakup/prepare (May/November)	61	30	61	30
6	Shutdown Days for Hauling	10	12	10	48
7	Shutdown Days for Harvesting	10	9	10	36
8	Harvest Volume (m^3)	750,000	1,500,000	750,000	1,500,000
9	Access Road (km)	300.00	600.00	300.00	600.00
10	Eligible Logging Days	153	121	153	121
11	Holidays/Sundays	37	29	37	29
12	Operation Days	106	83	106	56
13	Hauling Operation Days	106	80	106	44
14		**Unit Prices (\$/m^3)**			
15	Felling (\$/m^3)	3.12	3.11	3.50	3.48
16	Skidding (\$/m^3)	3.09	3.08	3.43	3.42
17	Delimbing (\$/m^3)	4.25	4.29	4.83	4.87
18	Loading (\$/m^3)	2.05	2.06	2.41	2.42
19	Hauling (\$/m^3)	8.21	6.12	8.71	6.61
20	Decompaction Cost ($/km)[a]	1,143.00	0.00	1,143.00	0.00
21	Clearing/Pilling ($/km)	3,557.05	2,124.04	3,840.72	2,407.72
22	Seedling/Planting Cost ($/ha)[b]	1078.00	0.00	1078.00	0.00
23		**Total Costs ($)**			
24	Harvesting Cost ($)	7,849,304	15,715,946	8,816,068	17,649,474
25	Road Building Cost ($)	1,067,114	1,274,423	1,152,217	1,444,629
26	Decompaction Cost ($)	342,900	0	342,900	0
27	Planting Cost ($)[1]	258,720	0	258,720	0
28	Hauling Cost ($)	6,155,316	9,179,827	6,531,095	9,914,226
29	Loading Cost ($)	1,538,040	3,093,649	1,804,507	3,626,584
30	Total Seasonal Costs ($)	17,211,393	29,263,844	18,905,508	32,634,913
31	**Total Annual Cost ($)**	**46,475,237**		**51,540,420**	
32	Idle Cost ($) - Hauling	347,142		833,513	
33	Idle Cost ($) - Loading	546,806		1,015,497	
34	Idle Cost ($) - Harvesting	2,556,462		4,406,595	
35	**Idle Cost ($) - Total**	**3,450,409**		**6,255,605**	
36	**Total Costs of Harvesting & Hauling (\$/m^3)**	20.72	18.66	22.87	20.79
37	**Total Unit Costs of Logging (\$/m^3)**	**22.95**	**19.51**	**25.21**	**21.76**
38		**Number of Machines**			
39	Felling	7	20	7	29
40	Skidding	9	25	9	37
41	Delimbing	14	40	14	58
42	Loading	5	12	5	18
43	Hauling	21	48	21	86
44	Excavator	3	5	3	7
45	[1] 8 meter wide, 1 km length of the road is 0.8 hectare. This conversion was used for seedling and planting of the access road.				
46	[a] Sessions & Sessions (1992)				
47	[b] USDA (2017)				

Appendix A.2 Cost calculation for feller buncher

	A	B	C	D
1		**Feller Buncher**		[a] Miyata (1980)
2	Time	**Base Year**		[b] Akay (1998)
3	**Production**	Summer	Winter	[c] Machine Finder (n.d.)a
4	Annual Production (m^3)	750,000	1,500,000	[d] Wenger (1984)
5	Days	106	83	[e] Smidth & Gallagher (2013)
6	Hours/Day	21	19	[f] Alberta Alis (n.d.)
7	Annual Available Hours	2,226	1,577	[g] obtained from contractor
8	Utilization Percentage [a]	65	65	
9	Annual Production Hours	1,447	1,025	
10	Expected Life (Years) [b]	5.00		
11	**Purchase Information**			
12	Equipment Purchase Cost ($) [c]	377,000		
13	Salvage Value (%) [b]	0.15		
14	Fuel Price ($) [d]	1.00		
15	Oil Lube Costs (%) [d]	0.10		
16	Insurance Costs (%) [d]	0.035		
17	Load Factor	0.25		
18	Salvage Value ($)	56,550		
19	Rate of Return on Total Capital	0.10		
20	Average Annual Equipment Value ($)	216,775		
21	Fuel Consumption (lt/hr) [e]	41.60	42.60	
22	**Ownership Costs**			
23	Depreciation ($/year)	64,090		
24	Insurance ($/year)	7,587		
25	Return on Capital ($/year)	21,678		
26	Annual Ownership Costs ($/year)	93,355		
27	Total Ownership Costs ($/year)	1,867,093		
28	**Total Ownership Unit Cost ($/$m^3$)**	0.83		
29	**Labor Costs**			
30	Straight Time	1,908	1,494	
31	Overtime Worked	318	83	
32	Wage ($/hr) [f]	29.29	29.29	
33	Overtime ($/hr)	43.94	43.94	
34	Seasonal Labor Costs ($)	69,857	47,406	
35	Add Employee Load (Benefits)	17,464	11,851	
36	Total Labour Costs ($)	87,321	59,257	
37	**Total Labor Unit Costs ($/$m^3$)**	1.23	1.18	
38	**Operation Costs**			
39	Fuel cost ($/hr)	41.60	42.60	
40	Oil/Lube Cost ($/hr)	4.16	4.26	
41	Fuel & Lube Cost ($/$m^3$)	0.09	0.03	
42	Repair & Maintenance Costs ($/year)	32,045		
43	Repair & Maintenance Costs ($/$m^3$)	0.264		
44	Total Operation Costs (Season)	75,510	55,316	
45	**Total Operation Unit Costs ($/$m^3$)**	1.06	1.10	
46	**Total Equipment Unit Costs (Seasonal) ($/$m^3$)**	***3.12***	***3.11***	
47	Number of Equipment	**7**	**20**	
48	Productivity (m^3/Pmh)[g]	61.35	61.35	
49	Availability (%)	0.80	0.80	
50	Productivity (m^3/Smh)	49.08	49.08	

Appendix A.3 Cost calculation for skidder

	A	B	C	D
1		**Skidder**		[a] Miyata (1980)
2	Time	**Base Year**		[b] Akay (1998)
3	**Production**	Summer	Winter	[c] Machine Finder (n.d.)a
4	Annual Production (m^3)	750,000	1,500,000	[d] Wenger (1984)
5	Days	106	83	[e] Smidth & Gallagher (2013)
6	Hours/Day	21	19	[f] Alberta Alis (n.d.)
7	Annual Available Hours	2,226	1,577	[g] obtained from contractor
8	Utilization Percentage [a]	70	70	
9	Annual Production Hours	1,558	1,104	
10	Expected Life (Years) [b]	4.00		
11	**Purchase Information**			
12	Equipment Purchase Cost ($) [c]	225,000		
13	Salvage Value (%) [b]	0.20		
14	Fuel Price ($) [d]	1.00		
15	Oil Lube Costs (%) [d]	0.10		
16	Insurance Costs (%) [d]	0.035		
17	Load Factor	0.25		
18	Salvage Value ($)	45,000		
19	Rate of Return on Total Capital	0.10		
20	Average Annual Equipment Value ($)	135,000		
21	Fuel Consumption (lt/hr) [e]	34.00	35.00	
22	**Ownership Costs**			
23	Depreciation ($/year)	45,000		
24	Insurance ($/year)	4,725		
25	Return on Capital ($/year)	13,500		
26	Annual Ownership Costs ($/year)	63,225		
27	Total Ownership Costs ($/year)	1,580,625		
28	**Total Ownership Unit Cost ($/m³)**	0.70		
29	**Labor Costs**			
30	Straight Time	1,908	1,494	
31	Overtime Worked	318	83	
32	Wage ($/hr) [f]	25.91	25.91	
33	Overtime ($/hr)	38.87	38.87	
34	Seasonal Labor Costs ($)	61,795	41,935	
35	Add Employee Load (Benefits)	15,449	10,484	
36	Total Labour Costs ($)	77,244	52,419	
37	**Total Labor Unit Costs ($/m³)**	1,29	1,23	
38	**Operation Costs**			
39	Fuel cost ($/hr)	34.00	35.00	
40	Oil/Lube Cost ($/hr)	3.40	3.50	
41	Fuel & Lube Cost ($/m³)	0.08	0.03	
42	Repair & Maintenance Costs ($/year)	27,000		
43	Repair & Maintenance Costs ($/m³)	0.263		
44	Total Operation Costs (Season)	66,112	48,636	
45	**Total Operation Unit Costs ($/m³)**	1.10	1.14	
46	**Total Equipment Unit Costs (Seasonal) ($/m³)**	***3.09***	***3.08***	
47	Number of Equipment	**9**	**25**	
48	Productivity (m³/Pmh)[g]	51.36	51.36	
49	Availability (%)	0.75	0.75	
50	Productivity (m³/Smh)	38.52	38.52	

Appendix A.4 Cost calculation for delimber

	A	B	C	D
1		**Delimber**		[a] Miyata (1980)
2	Time	**Base Year**		[b] Akay (1998)
3	**Production**	Summer	Winter	[c] Machine Finder (n.d.)b
4	Annual Production (m^3)	750,000	1,500,000	[d] Wenger (1984)
5	Days	106	83	[e] Smidth & Gallagher (2013)
6	Hours/Day	21	19	[f] Alberta Alis (n.d.)
7	Annual Available Hours	2,226	1,577	[g] obtained from contractor
8	Utilization Percentage [a]	90	90	
9	Annual Production Hours	2,003	1,419	
10	Expected Life (Years) [b]	5.00		
11	**Purchase Information**			
12	Equipment Purchase Cost ($) [c]	300,000		
13	Salvage Value (%) [b]	0.20		
14	Fuel Price ($) [d]	1.00		
15	Oil Lube Costs (%) [d]	0.10		
16	Insurance Costs (%) [d]	0.035		
17	Load Factor	0.25		
18	Salvage Value ($)	60,000		
19	Rate of Return on Total Capital	0.10		
20	Average Annual Equipment Value ($)	180,000		
21	Fuel Consumption (lt/hr) [e]	21.00	23.00	
22	**Ownership Costs**			
23	Depreciation ($/year)	48,000		
24	Insurance ($/year)	6,300		
25	Return on Capital ($/year)	18,000		
26	Annual Ownership Costs ($/year)	72,300		
27	Total Ownership Costs ($/year)	2,892,000		
28	**Total Ownership Unit Cost ($/m^3$)**	1.29		
29	**Labor Costs**			
30	Straight Time	1,908	1,494	
31	Overtime Worked	318	83	
32	Wage ($/hr) [f]	29.29	29.29	
33	Overtime ($/hr)	43.94	43.94	
34	Seasonal Labor Costs ($)	69,857	47,406	
35	Add Employee Load (Benefits)	17,464	11,851	
36	Total Labour Costs ($)	87,321	59,257	
37	**Total Labor Unit Costs ($/m^3$)**	1.79	1.71	
38	**Operation Costs**			
39	Fuel cost ($/hr)	21.00	23.00	
40	Oil/Lube Cost ($/hr)	2.10	2.30	
41	Fuel & Lube Cost ($/m^3$)	0.06	0.02	
42	Repair & Maintenance Costs ($/year)	38,400		
43	Repair & Maintenance Costs ($/m^3$)	0.461		
44	Total Operation Costs (Season)	57,423	44,634	
45	**Total Operation Unit Costs ($/m^3$)**	1.18	1.29	
46	**Total Equipment Unit Costs (Seasonal) ($/m^3$)**	***4.25***	***4.29***	
47	Number of Equipment	**14**	**40**	
48	Productivity (m^3/Pmh)[g]	34.79	34.79	
49	Availability (%)	0.70	0.70	
50	Productivity (m^3/Smh)	24.35	24.35	

Appendix A.5 Cost calculation for loader

	A	B	C	D
1		**Loader**		[a] Miyata (1980)
2	Time	**Base Year**		[b] Akay (1998)
3	**Production**	Summer	Winter	[c] Finning (n.d.)
4	Annual Production (m^3)	750,000	1,500,000	[d] Wenger (1984)
5	Days	106	83	[e] Smidth & Gallagher (2013)
6	Hours/Day	21	19	[f] Alberta Alis (n.d.)
7	Annual Available Hours	2,226	1,577	[g] obtained from contractor
8	Utilization Percentage [a]	60	60	
9	Annual Production Hours	1,336	946	
10	Expected Life (Years) [b]	5.00		
11	**Purchase Information**			
12	Equipment Purchase Cost ($) [c]	585,000		
13	Salvage Value (%) [b]	0.30		
14	Fuel Price ($) [d]	1.00		
15	Oil Lube Costs (%) [d]	0.10		
16	Insurance Costs (%) [d]	0.035		
17	Load Factor	0.25		
18	Salvage Value ($)	175,500		
19	Rate of Return on Total Capital	0.10		
20	Average Annual Equipment Value ($)	380,250		
21	Fuel Consumption (lt/hr) [e]	26.00	28.00	
22	**Ownership Costs**			
23	Depreciation ($/year)	81,900		
24	Insurance ($/year)	13,309		
25	Return on Capital ($/year)	38,025		
26	Annual Ownership Costs ($/year)	133,234		
27	Total Ownership Costs ($/year)	1,598,805		
28	**Total Ownership Unit Cost ($/$m^3$)**	0.71		
29	**Labor Costs**			
30	Straight Time	1,908	1,494	
31	Overtime Worked	318	83	
32	Wage ($/hr) [f]	29.29	29.29	
33	Overtime ($/hr)	43.94	43.94	
34	Seasonal Labor Costs ($)	69,857	47,406	
35	Add Employee Load (Benefits)	17,464	11,851	
36	Total Labour Costs ($)	87,321	59,257	
37	**Total Labor Unit Costs ($/$m^3$)**	0.81	0.78	
38	**Operation Costs**			
39	Fuel cost ($/hr)	26.00	28.00	
40	Oil/Lube Cost ($/hr)	2.60	2.80	
41	Fuel & Lube Cost ($/$m^3$)	0.05	0.02	
42	Repair & Maintenance Costs ($/year)	65,520		
43	Repair & Maintenance Costs ($/$m^3$)	0.356		
44	Total Operation Costs (Season)	57,213	44,032	
45	**Total Operation Unit Costs ($/$m^3$)**	0.53	0.58	
46	**Total Equipment Unit Costs (Seasonal) ($/$m^3$)**	***2.05***	***2.06***	
47	Number of Equipment	**5**	**12**	
48	Productivity (m^3/Pmh)[g]	95.00	95.00	
49	Availability (%)	0.85	0.85	
50	Productivity (m^3/Smh)	80.75	80.75	

Appendix A.6 Cost calculation for hauling truck (20 tons) – Hauling directly to the mill

	A	B	C	D
1		**Hauling Truck**		[a] Miyata (1980)
2	Time	**Base Year**		[b] Akay (1998)
3	**Production**	Summer	Winter	[c] Truck Paper (n.d.)
4	Annual Production (m^3)	750,000	1,500,000	[d] Wenger (1984)
5	Days	106	80	[e] Smidth & Gallagher (2013)
6	Hours/Day	21	19	[f] Alberta Alis (n.d.)
7	Annual Available Hours	2,226	1,520	[g] Total equipment cost includes operation costs and transportation costs which were calculated in Appendix A.9
8	Utilization Percentage [a]	80	80	
9	Annual Production Hours	1,781	1,216	
10	Expected Life (Years) [b]	6.00		[h] Truck productivity calculation is in Appendix A.9
11	**Purchase Information**			
12	Equipment Purchase Cost ($) [c]	100,000		
13	Salvage Value (%) [b]	0.15		
14	Fuel Price ($) [d]	1.00		
15	Oil Lube Costs (%) [d]	0.12		
16	Insurance Costs (%) [d]	0.035		
17	Load Factor	0.25		
18	Salvage Value ($)	15,000		
19	Rate of Return on Total Capital	0.10		
20	Average Annual Equipment Value ($)	57,500		
21	Fuel Consumption (lt/hr) [e]	26.20	28.00	
22	**Ownership Costs**			
23	Depreciation ($/year)	14,167		
24	Insurance ($/year)	2,013		
25	Return on Capital ($/year)	5,750		
26	Annual Ownership Costs ($/year)	21,929		
27	Total Ownership Costs ($/year)	1,052,600		
28	**Total Ownership Unit Cost ($/$m^3$)**	0.47		
29	**Labor Costs**			
30	Straight Time	1,908	1,494	
31	Overtime Worked	318	83	
32	Wage ($/hr) [f]	28.75	28.75	
33	Overtime ($/hr)	43.13	43.13	
34	Seasonal Labor Costs ($)	68,569	44,850	
35	Add Employee Load (Benefits)	17,142	11,213	
36	Total Labour Costs ($)	85,711	56,063	
37	**Total Labor Unit Costs ($/$m^3$)**	2.99	2.20	
38	**Operation Costs**			
39	Fuel cost ($/hr)	26.20	28.00	
40	Oil/Lube Cost ($/hr)	3.14	3.36	
41	Fuel & Lube Cost ($/$m^3$)	0.07	0.03	
42	Repair & Maintenance Costs ($/year)	11,333		
43	Repair & Maintenance Costs ($/$m^3$)	0.593		
44	Total Operation Costs (Season)	55,545	40,616	
45	**Total Operation Unit Costs ($/$m^3$)**	4.75	3.46	
46	**Total Equipment Unit Costs (Seasonal) ($/$m^3$)[g]**	***8.21***	***6.12***	
47	Number of Trips	**53**	**108**	
48	Number of Equipment	**21**	**48**	
49	Productivity (m^3/Pmh)[h]	7.09	10.22	
50	Availability (%)	0.90	0.90	
51	Productivity (m^3/Smh)	6.38	9.19	

Appendix A.7 Cost calculation for hauling truck (20 tons) – Hauling to satellite yard

	A	B	C	D
1		**Hauling Truck**		[a] Miyata (1980)
2	Time	**Base Year**		[b] Akay (1998)
3	**Production**	Summer	Winter	[c] Truck Paper (n.d.)
4	Annual Production (m^3)	750,000	1,500,000	[d] Wenger (1984)
5	Days	106	80	[e] Smidth & Gallagher (2013)
6	Hours/Day	21	19	[f] Alberta Alis (n.d.)
7	Annual Available Hours	2,226	1,520	[g] Total equipment cost includes operation costs and transportation costs which were calculated in Appendix A.10
8	Utilization Percentage [a]	80	80	
9	Annual Production Hours	1,781	1,216	
10	Expected Life (Years) [b]	6.00		[h] Truck productivity calculation is in Appendix A.10
11	**Purchase Information**			
12	Equipment Purchase Cost ($) [c]	100,000		
13	Salvage Value (%) [b]	0.15		
14	Fuel Price ($) [d]	1.00		
15	Oil Lube Costs (%) [d]	0.12		
16	Insurance Costs (%) [d]	0.035		
17	Load Factor	0.25		
18	Salvage Value ($)	15,000		
19	Rate of Return on Total Capital	0.10		
20	Average Annual Equipment Value ($)	57,500		
21	Fuel Consumption (lt/hr) [e]	26.20	28.00	
22	**Ownership Costs**			
23	Depreciation ($/year)	14,167		
24	Insurance ($/year)	2,013		
25	Return on Capital ($/year)	5,750		
26	Annual Ownership Costs ($/year)	21,929		
27	Total Ownership Costs ($/year)	65,788		
28	**Total Ownership Unit Cost ($/m^3)**	0.03		
29	**Labor Costs**			
30	Straight Time	1,908	1,494	
31	Overtime Worked	318	83	
32	Wage ($/hr) [f]	28.75	28.75	
33	Overtime ($/hr)	43.13	43.13	
34	Seasonal Labor Costs ($)	68,569	44,850	
35	Add Employee Load (Benefits)	17,142	11,213	
36	Total Labour Costs ($)	85,711	56,063	
37	**Total Labor Unit Costs ($/m^3)**	0.18	0.13	
38	**Operation Costs**			
39	Fuel cost ($/hr)	26.20	28.00	
40	Oil/Lube Cost ($/hr)	3.14	3.36	
41	Fuel & Lube Cost ($/m^3)	0.07	0.03	
42	Repair & Maintenance Costs ($/year)	11,333		
43	Repair & Maintenance Costs ($/m^3)	0.593		
44	Total Operation Costs (Season)	55,545	40,616	
45	**Total Operation Unit Costs ($/m^3)**	1.11	0.79	
46	**Total Equipment Unit Costs (Seasonal) ($/m^3)[g]**	***1.31***	***0.95***	
47	Number of Trips	**13**	**27**	
48	Number of Equipment	**2**	**3**	
49	Productivity (m^3/Pmh)[h]	29.05	41.85	
50	Availability (%)	0.90	0.90	
51	Productivity (m^3/Smh)	26.14	37.66	

Appendix A.8 Cost calculation for excavation to build access and in-block roads

	A	B	C	D
1		**Excavator**		[a] Miyata (1980)
2	Time	**Base Year**		[b] Akay (1998)
3	**Production**	Summer	Winter	[c] Finning (n.d.)
4	Annual Production (km)	300	600	[d] Wenger (1984)
5	Days	106	83	[e] Kenny (2013)
6	Hours/Day	21	19	[f] Alberta Alis (n.d.)
7	Annual Available Hours	2,226	1,577	[g] obtained from contractor
8	Utilization Percentage [a]	75	75	
9	Annual Production Hours	1,670	1,183	
10	Expected Life (Years) [b]	4.00		
11	**Purchase Information**			
12	Equipment Purchase Cost ($) [c]	440,000		
13	Salvage Value (%) [b]	0.15		
14	Fuel Price ($) [d]	1.00		
15	Oil Lube Costs (%) [d]	0.10		
16	Insurance Costs (%) [d]	0.035		
17	Load Factor	0.25		
18	Salvage Value ($)	66,000		
19	Rate of Return on Total Capital	0.10		
20	Average Annual Equipment Value ($)	253,000		
21	Fuel Consumption (lt/hr) [e]	41.60	43.00	
22	**Ownership Costs**			
23	Depreciation ($/year)	93,500		
24	Insurance ($/year)	8,855		
25	Return on Capital ($/year)	25,300		
26	Annual Ownership Costs ($/year)	127,655		
27	Total Ownership Costs ($/year)	638,275		
28	**Total Ownership Unit Cost ($/km)**	709.19		
29	**Labor Costs**			
30	Straight Time	1,908	1,494	
31	Overtime Worked	318	83	
32	Wage ($/hr) [f]	29.29	29.29	
33	Overtime ($/hr)	43.94	43.94	
34	Seasonal Labor Costs ($)	69,857	47,406	
35	Add Employee Load (Benefits)	17,464	11,851	
36	Total Labour Costs ($)	87,321	59,257	
37	**Total Labor Unit Costs ($/km)**	1,341.12	634.19	
38	**Operation Costs**			
39	Fuel cost ($/hr)	41.60	43.00	
40	Oil/Lube Cost ($/hr)	4.16	4.30	
41	Fuel & Lube Cost ($/km)	254.65	93.24	
42	Repair & Maintenance Costs ($/year)	74,800		
43	Repair & Maintenance Costs ($/km)	672,434		
44	Total Operation Costs (Season)	98,104	72,942	
45	**Total Operation Unit Costs ($/km)**	1,506.73	780.65	
46	**Total Equipment Unit Costs (Seasonal) ($/km)**	***3,557.05***	***2,124.04***	
47	Number of Equipment	**3**	**5**	
48	Productivity (km/Pmh)[g]	0.039	0.079	
49	Availability (%)	1.00	1.00	
50	Productivity (km/Smh)	0.039	0.079	

Appendix A.9 Hauling truck productivity – Hauling directly to the mill

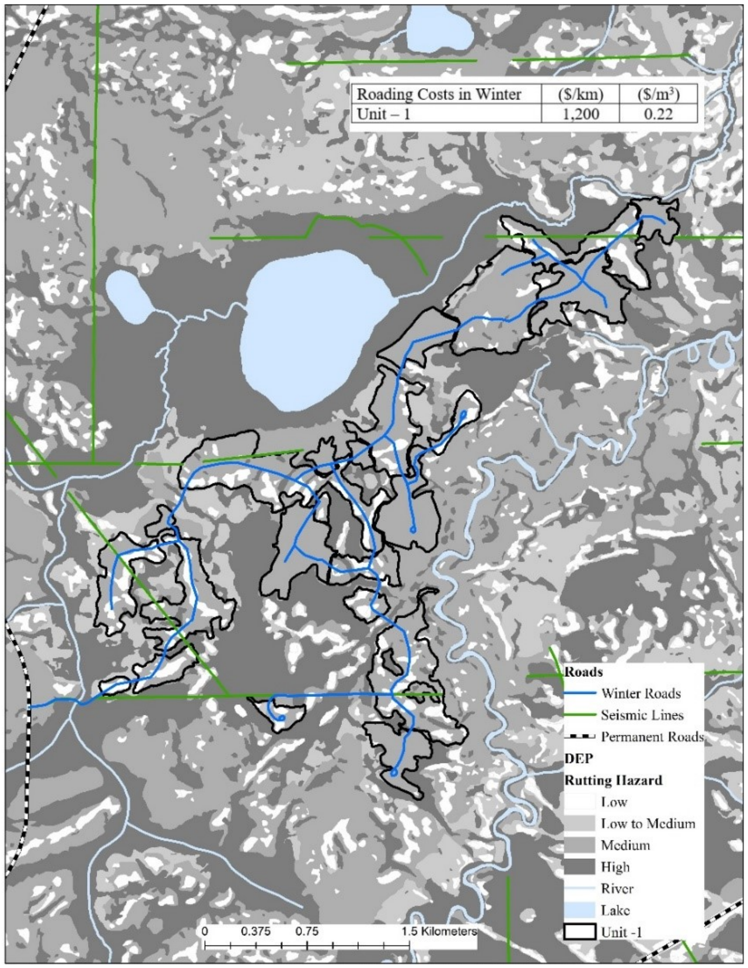
1	Truck Productivity & Cost of Truck Transportation			[a] Dratchev (2013)
2		Summer	Winter	[b] Sessions & Sessions (1992)
3	Hours/Day	21	19	
4	Haul distance (km)[1]	250		
5	Average speed (km/hr) (Unloaded/Loaded) [a]	85	55	
6	Load Size (tons)	27.3	39	
7	Load Size (m^3)	59	85	
8	Unloading time (mins) [b]	30		
9	Loading time (mins) [b]	20		
10	Total Trip (hr)	8		
11	Productivity (m^3/truck)	7.09	10.22	
12	Number of road trips in a day	3	2	
13	Cost per Standing Time ($/hr)	20		
14	Cost per Truck Running Time ($/hr)	30		
15		Summer	Winter	
16	Fixed Cost (Truck Standby for Loading and Unloading)	0.28	0.20	
17	Variable Cost (Truck Travel)	3.81	2.64	
18	Total Unit Cost[2] (without Operation Cost) ($/$m^3$)	***4.09***	***2.84***	
19				
20		Weight (tons)	Volume[3] (m^3)	
21	Tare Weight of Truck	20.0		
22	Gross Vehicle Weight Summer	47.3		
23	Gross Vehicle Weight Winter	59.3		
24	Payload Weight Summer[4]	27.3	59	
25	Payload Weight Winter[4]	39.3	85	
26				
27	[1] Average hauling distance to mill			
28	[2] Total unit cost in this section was calculated for based on trucks transportation			
29	[3] Wood load size was converted from US ton to m^3 for aspen			
30	[4] ARGH Industries Ltd (n.d.), Wood converter. Retrieved from: https://www.thecalculatorsite.com/conversions/substances/wood.php			

Appendix A.10 Hauling truck productivity – Hauling to the satellite yard

1	Truck Productivity & Cost of Truck Transportation			[a] Dratchev (2013) [b] Sessions & Sessions (1992)
2		Summer	Winter	
3	Hours/Day	21	19	
4	Haul distance (km)[1]	40		
5	Average speed (km/hr) (Unloaded/Loaded) [a]	85	55	
6	Load Size (tons)	27.3	39	
7	Load Size (m^3)	59	85	
8	Unloading time (mins) [b]	30		
9	Loading time (mins) [b]	20		
10	Total Trip (hr)	8		
11	Productivity (m^3/truck)	29.05	41.85	
12	Number of road trips in a day	10	9	
13	Cost per Standing Time ($/hr)	20		
14	Cost per Truck Running Time ($/hr)	30		
15		Summer	Winter	
16	Fixed Cost (Truck Standby for Loading and Unloading)	0.28	0.20	
17	Variable Cost (Truck Travel)	0.61	0.42	
18	Total Unit Cost[2] (without Operation Cost) ($/$m^3$)	***0.89***	***0.62***	
19				
20		Weight (tons)	Volume[3] (m^3)	
21	Tare Weight of Truck	20.0		
22	Gross Vehicle Weight Summer	47.3		
23	Gross Vehicle Weight Winter	59.3		
24	Payload Weight Summer[4]	27.3	59	
25	Payload Weight Winter[4]	39.3	85	
26				
27	[1] Average hauling distance to mill			
28	[2] Total unit cost in this section was calculated for based on trucks transportation			
29	[3] Wood load size was converted from US ton to m^3 for aspen			
30	[4] ARGH Industries Ltd (n.d.), Wood converter. Retrieved from: https://www.thecalculatorsite.com/conversions/substances/wood.php			

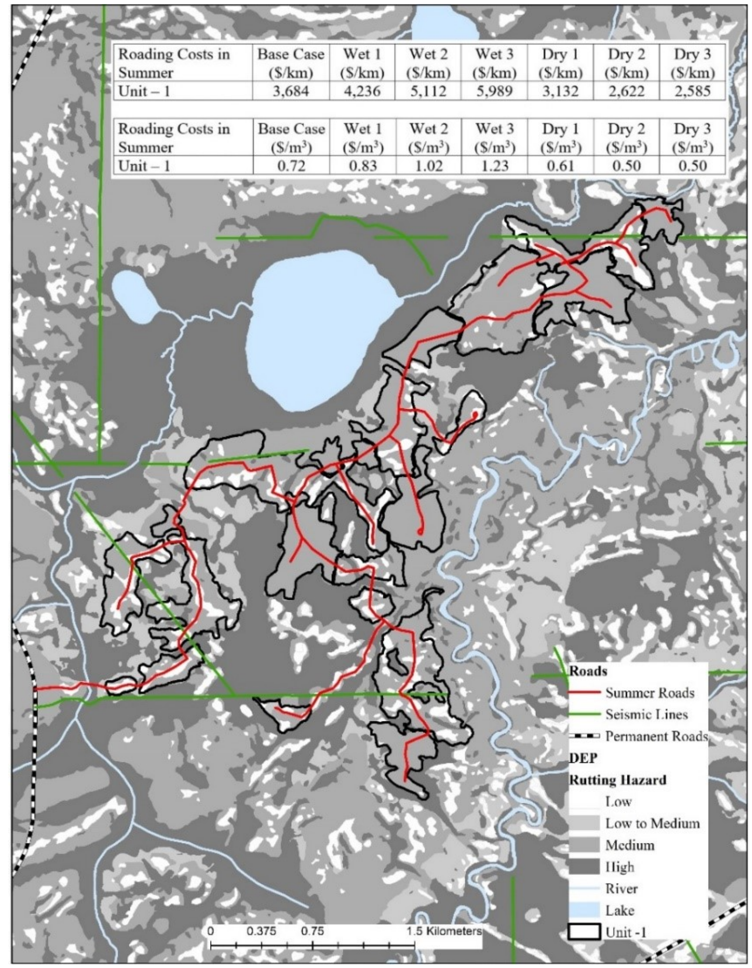
Appendix B Summer and winter forest road construction

Appendix B.1 Road layouts for unit-1 that were designed for winter/summer logging seasons and construction costs (base case, wet and dry scenarios)



Roading Costs in Winter	($/km)	($/m^3)
Unit – 1	1,200	0.22

a. Road network and construction cost in winter for unit-1

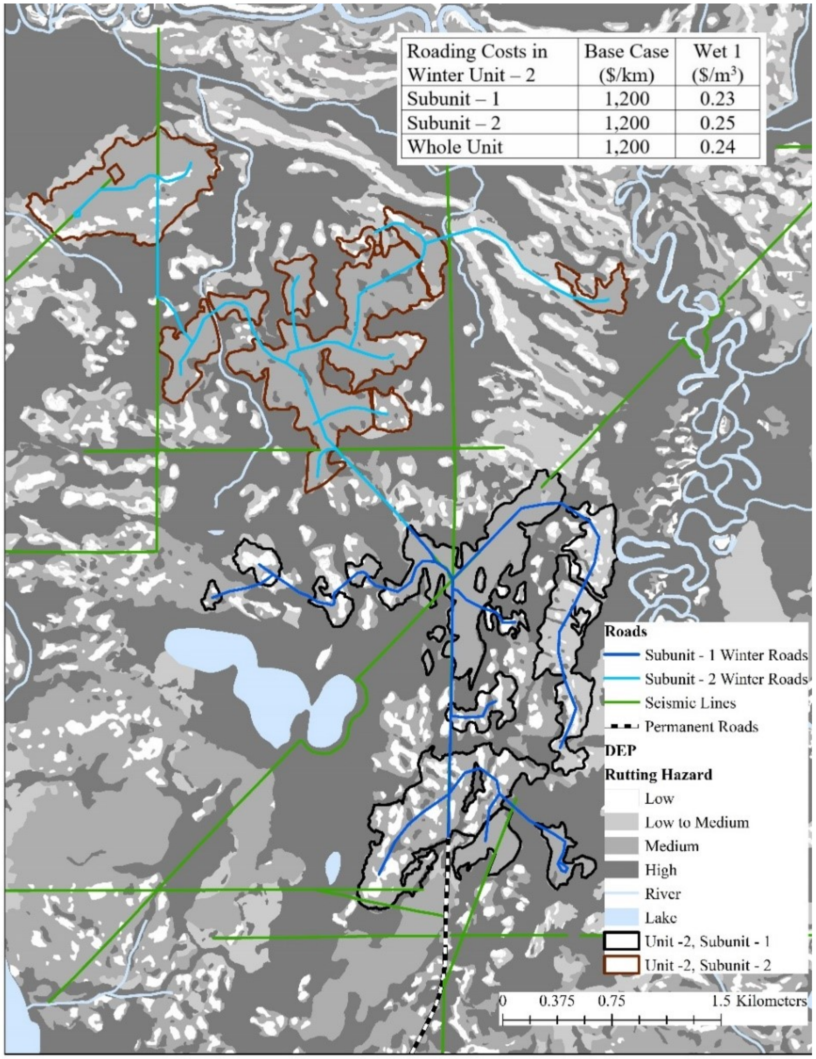


Roading Costs in Summer	Base Case ($/km)	Wet 1 ($/km)	Wet 2 ($/km)	Wet 3 ($/km)	Dry 1 ($/km)	Dry 2 ($/km)	Dry 3 ($/km)
Unit – 1	3,684	4,236	5,112	5,989	3,132	2,622	2,585

Roading Costs in Summer	Base Case ($/m^3)	Wet 1 ($/m^3)	Wet 2 ($/m^3)	Wet 3 ($/m^3)	Dry 1 ($/m^3)	Dry 2 ($/m^3)	Dry 3 ($/m^3)
Unit – 1	0.72	0.83	1.02	1.23	0.61	0.50	0.50

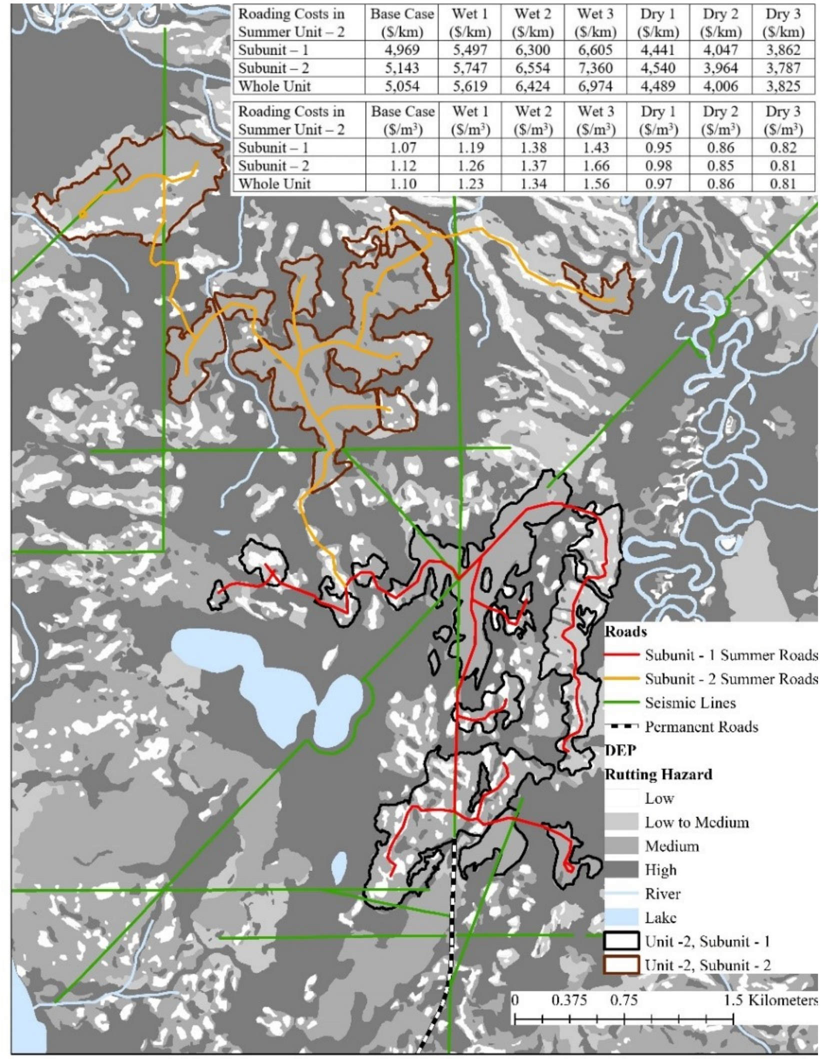
b. Road network and construction cost in summer for unit-1

Appendix B.2 Road layouts for unit-2 that were designed for winter/summer logging seasons and construction costs (base case, wet and dry scenarios)



Roading Costs in Winter Unit – 2	Base Case ($/km)	Wet 1 ($/m³)
Subunit – 1	1,200	0.23
Subunit – 2	1,200	0.25
Whole Unit	1,200	0.24

a. Road network and construction cost in winter for unit-2

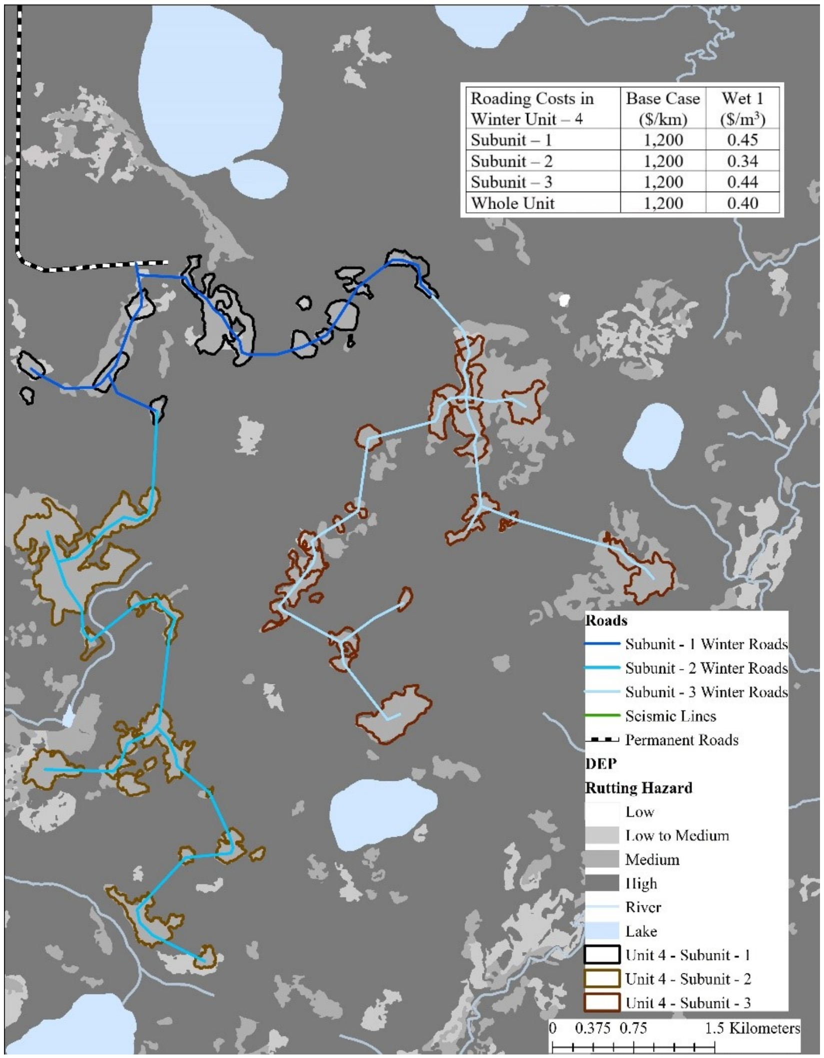


Roading Costs in Summer Unit – 2	Base Case ($/km)	Wet 1 ($/km)	Wet 2 ($/km)	Wet 3 ($/km)	Dry 1 ($/km)	Dry 2 ($/km)	Dry 3 ($/km)
Subunit – 1	4,969	5,497	6,300	6,605	4,441	4,047	3,862
Subunit – 2	5,143	5,747	6,554	7,360	4,540	3,964	3,787
Whole Unit	5,054	5,619	6,424	6,974	4,489	4,006	3,825

Roading Costs in Summer Unit – 2	Base Case ($/m³)	Wet 1 ($/m³)	Wet 2 ($/m³)	Wet 3 ($/m³)	Dry 1 ($/m³)	Dry 2 ($/m³)	Dry 3 ($/m³)
Subunit – 1	1.07	1.19	1.38	1.43	0.95	0.86	0.82
Subunit – 2	1.12	1.26	1.37	1.66	0.98	0.85	0.81
Whole Unit	1.10	1.23	1.34	1.56	0.97	0.86	0.81

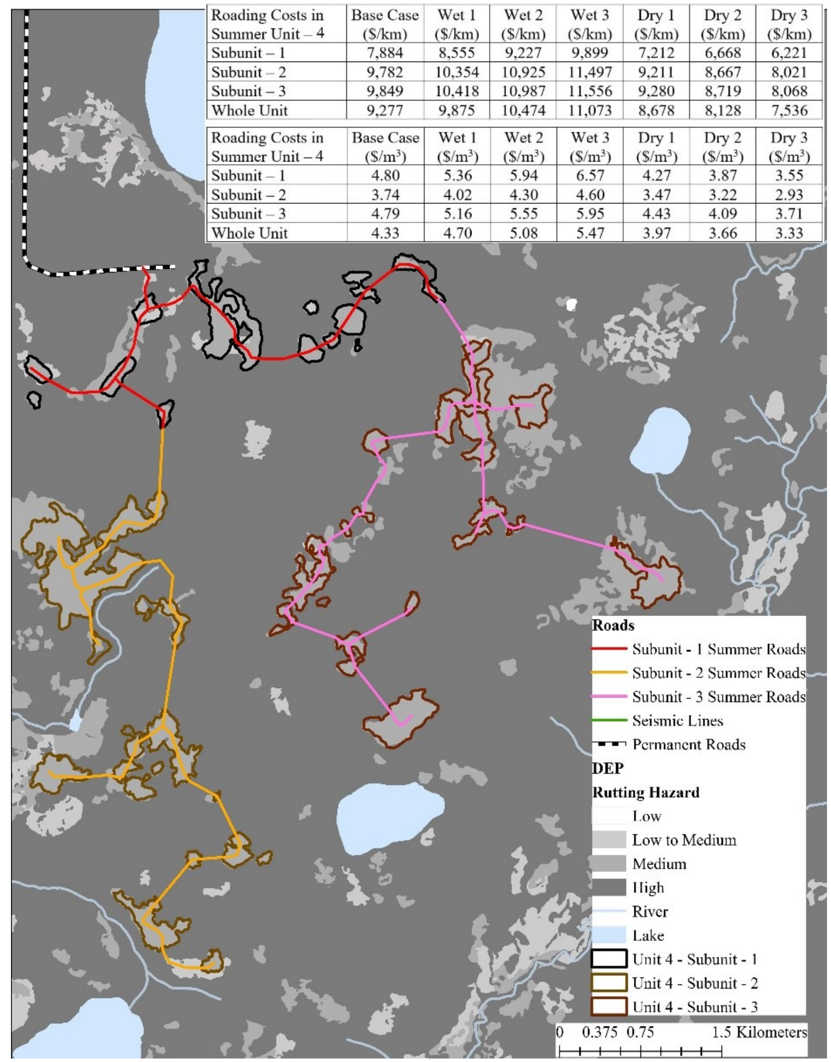
b. Road network and construction costs in summer for unit-2

Appendix B.3 Road layouts for unit-4 that were designed for winter/summer logging seasons and construction costs (base case, wet and dry scenarios)



Roading Costs in Winter Unit – 4	Base Case ($/km)	Wet 1 ($/m^3)
Subunit – 1	1,200	0.45
Subunit – 2	1,200	0.34
Subunit – 3	1,200	0.44
Whole Unit	1,200	0.40

a. Road network and construction cost in winter for unit-4



Roading Costs in Summer Unit – 4	Base Case ($/km)	Wet 1 ($/km)	Wet 2 ($/km)	Wet 3 ($/km)	Dry 1 ($/km)	Dry 2 ($/km)	Dry 3 ($/km)
Subunit – 1	7,884	8,555	9,227	9,899	7,212	6,668	6,221
Subunit – 2	9,782	10,354	10,925	11,497	9,211	8,667	8,021
Subunit – 3	9,849	10,418	10,987	11,556	9,280	8,719	8,068
Whole Unit	9,277	9,875	10,474	11,073	8,678	8,128	7,536

Roading Costs in Summer Unit – 4	Base Case ($/m^3)	Wet 1 ($/m^3)	Wet 2 ($/m^3)	Wet 3 ($/m^3)	Dry 1 ($/m^3)	Dry 2 ($/m^3)	Dry 3 ($/m^3)
Subunit – 1	4.80	5.36	5.94	6.57	4.27	3.87	3.55
Subunit – 2	3.74	4.02	4.30	4.60	3.47	3.22	2.93
Subunit – 3	4.79	5.16	5.55	5.95	4.43	4.09	3.71
Whole Unit	4.33	4.70	5.08	5.47	3.97	3.66	3.33

b. Road network and construction cost in summer for unit-4

Appendix B.4 Rutting hazard distribution (hectares) of the cutblocks within the planning units

		High	Medium	Low to Medium	Low	Total area (ha)	Total Harvest Volume (m^3)
Harvesting Unit-1		15	277	6	50	348	87,000
Harvesting Unit-2	Subunit-1	22	123	38	27	210	52,500
	Subunit-2	12	168	9	10	199	49,750
	Total	34	291	47	37	409	102,250
Harvesting Unit-3	Subunit-1	10	160	17	24	211	52,750
	Subunit-2	15	235	6	16	272	68,000
	Subunit-3	7	47	25	10	89	22,250
	Total	32	442	48	50	572	143,000
Harvesting Unit-4	Subunit-1	9	54	5	0	68	17,000
	Subunit-2	14	121	0	0	135	33,750
	Subunit-3	9	99	1	0	109	27,250
	Total	32	274	6	0	312	78,000

Appendix B.5 DEP Mapped rutting hazard distribution of summer road layouts

		High	Medium	Low to Medium	Low	Total summer road length (metres)	Corduroy road length (metres)	Total winter road length (metres)
Harvesting Unit-1		346	9,529	772	6,063	16,710	1,338	16,224
Harvesting Unit-2	Subunit-1	1,119	4,776	1,627	3,326	10,848	1,678	10,249
	Subunit-2	1,020	6,666	316	2,353	10,355	1,702	10,275
	Total	2,139	11,442	1,943	5,679	21,203	3,380	20,524
Harvesting Unit-3	Subunit-1	570	7,461	1,484	3,175	12,690	1,390	12,156
	Subunit-2	62	5,419	938	1,161	7,580	651	6,934
	Subunit-3	525	1,952	3,556	1,876	7,909	898	6,649
	Total	1,157	14,832	5,978	6,212	28,179	2,939	25,739
Harvesting Unit-4	Subunit-1	2,073	5,057	1,177	0	8,307	2,638	6,265
	Subunit-2	3,902	6,553	344	0	10,799	4,575	9,656
	Subunit-3	3,892	6,691	103	0	10,686	4566	9,986
	Total	9,867	18,301	1,624	0	29,792	11,779	25,907
Total study area						95,884	19,435	88,395

Appendix B.6 Corduroy lengths in metres for different scenarios

		Base Case	Wet-1	Wet-2	Wet-3	Dry-1	Dry-2	Dry-3
Harvesting Unit-1		1,338	1,853	2,671	3,489	822	346	311
Harvesting Unit-2	Subunit-1	1,678	1,998	2,485	2,971	1,358	1,119	1,007
	Subunit-2	1,702	2,052	2,518	2,985	1,353	1,020	918
	Total	3,380	4,050	5,003	5,956	2,711	2,139	1,925
Harvesting Unit-3	Subunit-1	1,390	1,838	2,444	3,050	943	570	513
	Subunit-2	651	969	1,345	1,720	333	62	56
	Subunit-3	898	1,173	1,543	1,912	623	525	473
	Total	2,939	3,980	5,331	6,682	1,899	1,157	1,041
Harvesting Unit-4	Subunit-1	2,638	2,949	3,261	3,573	2,326	2,073	1,866
	Subunit-2	4,575	4,919	5,264	5,609	4,230	3,902	3,512
	Subunit-3	4,566	4,906	5,246	5,585	4,227	3,892	3,503
	Total	11,779	12,775	13,771	14,767	10,782	9,867	8,880
Total		19,435	22,656	26,775	30,894	16,214	13,509	12,158

Appendix C Frozen highway conditions and highway hauling costs

Appendix C.1 Hauling cost calculator – Directly to the mill

	A	B	C	D
1	2020 Western Star 4900SA	Hauling Truck		[a] Miyata (1980)
2	Time	Base Year		[b] Akay (1998)
3	**Production**	Summer	Winter	[c] Truck Paper (n.d.)
4	Annual Production (m^3)	750,000	1,500,000	[d] Wenger (1984)
5	Days	153	104	[e] Smidth & Gallagher (2013)
6	Hours/Day	21	19	[f] Alberta Alis (n.d.)
7	Annual Available Hours	3,213	1,976	
8	Utilization Percentage [a]	80	80	
9	Annual Production Hours	2,570	1,581	
10	Expected Life (Years) [b]	6.00		
11	**Purchase Information**			
12	Equipment Purchase Cost ($) [c]	300,000		
13	Salvage Value (%) [b]	0.15		
14	Fuel Price ($) [d]	1.00		
15	Oil Lube Costs (%) [d]	0.12		
16	Insurance Costs (%) [d]	0.035		
17	Load Factor	0.25		
18	Salvage Value ($)	45,000		
19	Rate of Return on Total Capital	0.10		
20	Average Annual Equipment Value ($)	172,500		
21	Fuel Consumption (lt/hr) [e]	26.20	28.00	
22	**Ownership Costs**			
23	Depreciation ($/year)	42,500		
24	Insurance ($/year)	6,038		
25	Return on Capital ($/year)	17,250		
26	Annual Ownership Costs ($/year)	65,788		
27	Total Ownership Costs ($/year)	855,238	1,842,050	
28	**Total Ownership Unit Cost ($/m³)**	1.14	1.23	
29	**Labor Costs**			
30	Straight Time	2,754	1,872	
31	Overtime Worked	459	104	
32	Wage ($/hr) [f]	28.75	28.75	
33	Overtime ($/hr)	43.13	43.13	
34	Seasonal Labor Costs ($)	98,972	58,305	
35	Add Employee Load (Benefits)	24,743	14,576	
36	Total Labour Costs ($)	123,715	72,881	
37	**Total Labor Unit Costs ($/m³)**	2.61	1.66	
38	**Operation Costs**			
39	Fuel cost ($/hr)	26.20	28.00	
40	Oil/Lube Cost ($/hr)	3.14	3.36	
41	Fuel & Lube Cost ($/$m^3$)	0.07	0.03	
42	Repair & Maintenance Costs ($/year)	34,000		
43	Repair & Maintenance Costs ($/$m^3$)	1.19	0.72	
44	Total Operation Costs (Season)	89,668	59,255	
45	**Total Operation Unit Costs ($/m³)**	5.11	3.05	
46	**Total Equipment Unit Costs (Seasonal) ($/m³)**	***8.87***	***5.94***	
47	Number of Trips	35	67	
48	Number of Equipment	**13**	**28**	
49	Productivity (m^3/Pmh)	7.59	12.60	
50	Availability (%)	0.90	0.90	
51	Productivity (m^3/Smh)	6.83	11.34	

	Highway Only – Hauling to Mill			
1	Truck Productivity & Cost of Truck Transportation			
2		Summer	Winter	[a] Sessions & Sessions (1992)
3	Hours/Day	21	19	
4	Haul distance (km)[1]	250		
5	Average speed (km/hr) (Unloaded/Loaded)	90	60	
6	Load Size (tons)	27.3	45.4	
7	Load Size (m^3)	59	98	
8	Unloading time (mins) [a]	30		
9	Loading time (mins) [a]	20		
10	Total Trip (hr)	8		
11	Productivity (m^3/truck)	7.59	12.60	
12	Number of road trips in a day	3	2	
13	Cost per Standing Time ($/hr)	20		
14	Cost per Truck Running Time ($/hr)	30		
15		Summer	Winter	
16	Fixed Cost (Truck Standby for Loading and Unloading)	0.28	0.20	
17	Variable Cost (Truck Travel)	3.53	2.13	
18	Total Unit Cost[2] (without Operation Cost) ($/$m^3$)	**3.81**	**2.30**	
19				
20		Weight (tons)	Volume[3] (m^3)	
21	Tare Weight of Truck	20.0		
22	Gross Vehicle Weight Summer	47.3		
23	Gross Vehicle Weight Winter	59.3		
24	Payload Weight Summer[4]	27.3	59	
25	Payload Weight Winter[4]	45.4	85	
26				
27	[1] Average hauling distance to mill			
28	[2] Total unit cost in this section was calculated for based on trucks transportation			
29	[3] Wood load size was converted from US ton to m^3 for aspen			
30	[4] ARGH Industries Ltd (n.d.), Wood converter. Retrieved from: https://www.thecalculatorsite.com/conversions/substances/wood.php			

Appendix C.2 Hauling cost calculator – Directly to satellite yard

	A	B	C	D
1	2020 Western Star 4900SA	**Hauling Truck**		[a] Miyata (1980)
2	Time	**Base Year**		[b] Akay (1998)
3	**Production**	Summer	Winter	[c] Truck Paper (n.d.)
4	Annual Production (m^3)	750,000	1,500,000	[d] Wenger (1984)
5	Days	153	104	[e] Smidth & Gallagher (2013)
6	Hours/Day	21	19	[f] Alberta Alis (n.d.)
7	Annual Available Hours	3,213	1,976	
8	Utilization Percentage [a]	80	80	
9	Annual Production Hours	2,570	1,581	
10	Expected Life (Years) [b]	6.00		
11	**Purchase Information**			
12	Equipment Purchase Cost ($) [c]	300,000		
13	Salvage Value (%) [b]	0.15		
14	Fuel Price ($) [d]	1.00		
15	Oil Lube Costs (%) [d]	0.12		
16	Insurance Costs (%) [d]	0.035		
17	Load Factor	0.25		
18	Salvage Value ($)	45,000		
19	Rate of Return on Total Capital	0.10		
20	Average Annual Equipment Value ($)	172,500		
21	Fuel Consumption (lt/hr) [e]	26.20	28.00	
22	**Ownership Costs**			
23	Depreciation ($/year)	42,500		
24	Insurance ($/year)	6,038		
25	Return on Capital ($/year)	17,250		
26	Annual Ownership Costs ($/year)	65,788		
27	Total Ownership Costs ($/year)	65,788	131,575	
28	**Total Ownership Unit Cost ($/m³)**	0.09	0.09	
29	**Labor Costs**			
30	Straight Time	2,754	1,872	
31	Overtime Worked	459	104	
32	Wage ($/hr) [f]	28.75	28.75	
33	Overtime ($/hr)	43.13	43.13	
34	Seasonal Labor Costs ($)	98,972	58,305	
35	Add Employee Load (Benefits)	24,743	14,576	
36	Total Labour Costs ($)	123,715	72,881	
37	**Total Labor Unit Costs ($/m³)**	0.16	0.10	
38	**Operation Costs**			
39	Fuel cost ($/hr)	26.20	28.00	
40	Oil/Lube Cost ($/hr)	3.14	3.36	
41	Fuel & Lube Cost ($/$m^3$)	0.07	0.03	
42	Repair & Maintenance Costs ($/year)	34,000		
43	Repair & Maintenance Costs ($/$m^3$)	0.30	0.18	
44	Total Operation Costs (Season)	89,668	59,255	
45	**Total Operation Unit Costs ($/m³)**	1.25	0.72	
46	**Total Equipment Unit Costs (Seasonal) ($/m³)**	***1.50***	***0.92***	
47	Number of Trips	9	17	
48	Number of Equipment	**1**	**2**	
49	Productivity (m^3/Pmh)	30.34	50.40	
50	Availability (%)	0.90	0.90	
51	Productivity (m^3/Smh)	27.31	45.36	

	Highway Only – Hauling to Satellite Yard			
1	Truck Productivity & Cost of Truck Transportation			
2		Summer	Winter	[a] Sessions & Sessions (1992)
3	Hours/Day	21	19	
4	Haul distance (km)[1]	40		
5	Average speed (km/hr) (Unloaded/Loaded)	90	60	
6	Load Size (tons)	27.3	45.4	
7	Load Size (m^3)	59	98	
8	Unloading time (mins) [a]	30		
9	Loading time (mins) [a]	20		
10	Total Trip (hr)	8		
11	Productivity (m^3/truck)	30.34	50.40	
12	Number of road trips in a day	11	10	
13	Cost per Standing Time ($/hr)	20		
14	Cost per Truck Running Time ($/hr)	30		
15		Summer	Winter	
16	Fixed Cost (Truck Standby for Loading and Unloading)	0.28	0.20	
17	Variable Cost (Truck Travel)	0.56	0.34	
18	Total Unit Cost[2] (without Operation Cost) ($/$m^3$)	**0.85**	**0.51**	
19				
20		Weight (tons)	Volume[3] (m^3)	
21	Tare Weight of Truck	20.0		
22	Gross Vehicle Weight Summer	47.3		
23	Gross Vehicle Weight Winter	59.3		
24	Payload Weight Summer[4]	27.3	59	
25	Payload Weight Winter[4]	45.4	85	
26				
27	[1] Average hauling distance to mill			
28	[2] Total unit cost in this section was calculated for based on trucks transportation			
29	[3] Wood load size was converted from US ton to m^3 for aspen			
30	[4] ARGH Industries Ltd (n.d.), Wood converter. Retrieved from: https://www.thecalculatorsite.com/conversions/substances/wood.php			

Appendix C.3 RMSE values for site specific models for each monitoring sites along with cross comparison of model structures from each sites applied to the two other sites. The variables of the Conklin like model were eventually used as the prediction models developed for the Slave Lake and Manning sites. Coefficients of the final model are in Appendix C.5

		Conklin Predictions	
Models	**Conklin Original Model**	**Slave Lake Like Model**	**Manning Like Model**
15 cm	2.178	2.819	2.672
30 cm	2.257	2.658	2.344
60 cm	1.496	2.193	1.825
80 cm	1.464	1.952	1.790

		Slave Lake Predictions	
Models	**Slave Lake Original Model**	**Conklin Like Model**	**Manning Like Model**
15 cm	**1.836**	**1.844**	1.988
30 cm	**1.828**	**1.849**	2.065
60 cm	**1.484**	**1.484**	1.812
80 cm	**1.406**	**1.406**	1.767

		Manning Predictions	
Models	**Manning Original Model**	**Conklin Like Model**	**Slave Lake Like Model**
15 cm	**1.962**	**1.962**	2.081
30 cm	**1.762**	**1.761**	1.944
60 cm	**1.416**	**1.416**	2.266
80 cm	**1.322**	**1.324**	2.311

Second columns of tables represent RMSE values of site specific models. Variables from Conklin site model used to predict temperature at the depth of 15 cm, 30 cm, 60 cm and 80 cm because RMSE values of Conklin like model (red color) had little difference with original site specific models (bold).

Appendix C.4 Cumulative percentage of variance explained by the 12 regression models for each monitoring sites.

Percent of variance explained by the final regression models (Conklin-like Model)			
	Conklin	Slave Lake	Manning
15 cm	92.3	94.7	95.1
30 cm	90.9	94.1	95.1
60 cm	88.3	87.2	89.4
80 cm	86.4	85.9	88.8

For thawed condition, we used four variables because they were sufficient to explain percentage of the variance in the original data. For example, three-day average temperature, thawing degree days, freezing degree days and minimum temperature were used to predict the soil temperature at the depth of 15 cm for the Conklin location explains 92.3 % of the variance. For freeze up, we used five components (three-day average temperature, thawing degree days, freezing degree days, minimum daily temperature and average daily temperature) to explain variance of the data.

Appendix C.5 Coefficient of variables for the final model, at each depth and each monitoring site.

Conklin	a	b	c	d	e	f
15 cm	-1.362286	0.767102	0.003224	-0.003039	-0.063188	0
30 cm	-1.326114	0.757690	0.003169	-0.003100	-0.094189	0
60 cm	1.684587	0.465410	-0.006866	-0.006482	0.103615	-0.267769
80 cm	1.985917	0.352738	-0.007560	-0.004876	0.080331	-0.228291

Slave Lake	a	b	c	d	e	f
15 cm	-2.914530	0.702816	0.002428	0.038968	-0.044619	0
30 cm	-3.419028	0.665079	0.002251	0.042355	-0.069274	0
60 cm	2.007216	0.443569	-0.007513	-0.034787	0.083309	-0.198694
80 cm	2.598668	0.310081	-0.008872	-0.029858	0.067556	-0.172624

Manning	a	b	c	d	e	f
15 cm	-3.382335	0.599959	0.003203	0.039215	0.061323	0
30 cm	-3.989537	0.573355	0.002755	0.037392	0.011657	0
60 cm	1.740735	0.423821	-0.007235	-0.006928	0.055548	-0.177236
80 cm	2.414611	0.298031	-0.008243	-0.005555	0.045065	-0.160296

$$Tp_{15} = a_{15} + b_{15}A_p + c_{15}F_{dd} + d_{15}T_{dd} + e_{15}T_{min}$$

$$Tp_{30} = a_{30} + b_{30}A_p + c_{30}F_{dd} + d_{30}T_{dd} + e_{30}T_{min}$$

$$Tp_{60} = a_{60} + b_{60}A_p + c_{60}F_{dd} + d_{60}T_{dd} + e_{60}T_{min} + f_{60}T_{ave}$$

$$Tp_{80} = a_{80} + b_{80}A_p + c_{80}F_{dd} + d_{80}T_{dd} + e_{80}T_{min} + f_{80}T_{ave}$$

Tp_{15}: predicted soil/pavement temperature at 15 cm depth (°C),

Tp_{30}: predicted soil/pavement temperature at 30 cm depth (°C),

Tp_{60} : predicted soil/pavement temperature at 60 cm depth (°C),

Tp_{80} : predicted soil/pavement temperature at 80 cm depth (°C),

a_i : intercept coefficient for prediction of depth temperature i (15, 30, 60 and 80 cm),

b_i : three-day average temperature coefficient for prediction of depth temperature i,

A_p : three-day average temperature

c_i : freezing degree days coefficient for prediction of depth temperature i,

F_{dd} : freezing degree days

d_i : thawing degree days coefficient for prediction of depth temperature i,

T_{dd} : thawing degree days

e_i : minimum air temperature coefficient for prediction of depth temperature i,

T_{min} : minimum air temperature

f_i : average air temperature coefficient for prediction of depth temperature i,

T_{ave} : average air temperature