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Impact of Shortened Winter Road Access on Costs of Forest Operations

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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 labor 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 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 1.6% to 2.5% in 2030s, 2.8% to 5.3% in the 2050s and 4.8% to 10.9% in the 2080s 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 1.8% to 2.8% in the 2030s, 3.1% to 5.7% in the 2050s and 5.2% to 11.4% in the 2080s. Using satellite yards, however, will provide year-around employment for hauling truckers and more consistent and reliable hauling operations.

Keywords: winter logging; climate change; logging cost; winter hauling; logging cost calculator

1. Introduction

The boreal region in Canada consists of areas of upland forested land interspersed with peatlands [1] 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 [2]. 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 [3] 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 [4] will be a financial challenge to forestry companies [5] 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, habitat, aesthetics, and economic efficiency [6]. 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 [7]. Frozen soil conditions also avoid soil degradation from rutting or soil compaction from heavy machines [8,9]. Even roads within cut-blocks 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 soil 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 [7] 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 5.5 °C between 1950 and 2010 [10]. The mean winter temperature in this area is predicted to increase a further 1 °C to 3 °C by 2030s, 2 °C to 5 °C by the 2050s and 3 °C to 8 °C by 2080 (climateNA [11], LarsWG [12], Daymet [13]).

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) [14]. Rittenhouse & Rissman [15] 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 [16], e.g., in Saskatchewan in 2005–2006, winter operations did not start until January [17], or 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 labor, using satellite yards [18], increased investment in permanent (all weather) roads [19], more planning and harvesting summer accessible areas [20], and operating at night when the overnight temperatures help maintain frozen soils [21].

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 [22]. 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 labor needs if warming trends increase to those projected by general circulation models. If there are fewer frozen days, more equipment and labor 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 at three different 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. Materials and Methods

2.1. 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 Albertaat 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 1,400,000 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 imperfectly 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.

2.2. 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 used 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 in the 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. Historical Weather Data

We used the Daymet [13] dataset to obtain the mean daily and range of daily temperature for 1960 to 1980 and for 1995 to 2015 (Figure 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.

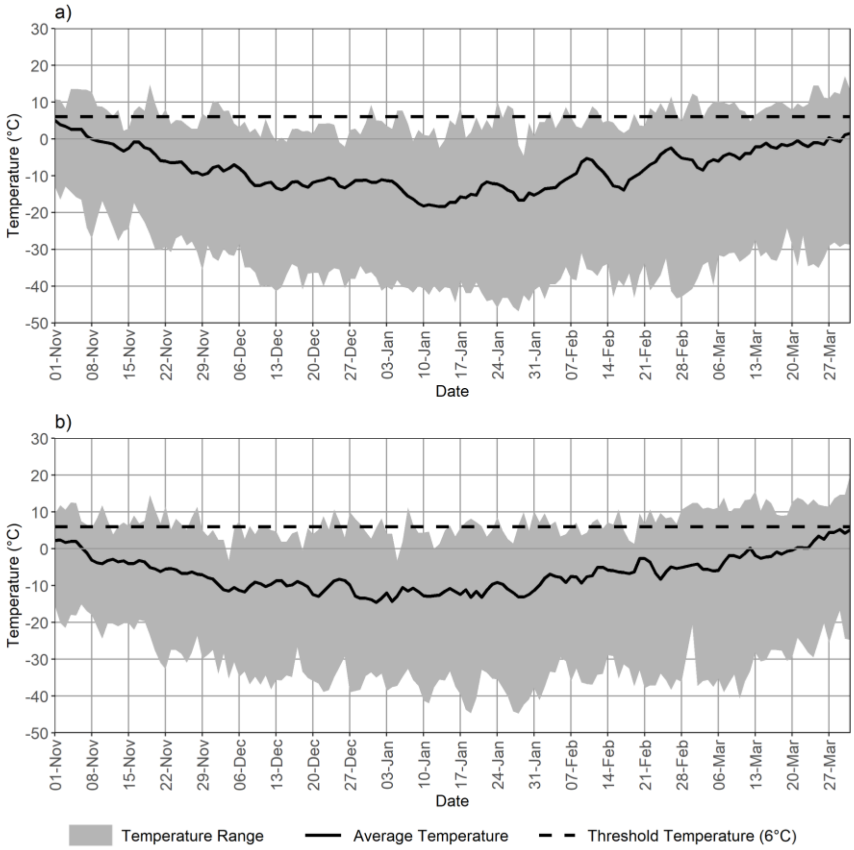

Figure 1. Range and average daily temperature for the period between (**a**) 1960 and 1980 (**b**) 1995 and 2015. The upper range is the extreme high and the lower range is the extreme low temperatures for each day of this 20 year period. Note, however, that every extreme high point above 6 °C is a shut-down day, but these did not all occur on the same year.

2.4. Future Climate

We chose three Representative Concentration Pathways (RCPs) [23], the 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 [24]. 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 [25]. 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 [26].

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. [27,28] showed that—HadGEM2-ES received a higher pattern correlation coefficient and lower bias and errors than the other models.

We used the Lars-WG [12] stochastic downscaling weather generator model (based on Markovia Chain [29] that produces daily maximum and minimum temperatures projections for the 2030s (2020 and 2039), 2050s (2040–2059) and 2080s (2070–2089); these are climate projections from the fifth phase of the Coupled Model Intercomparison Project (CMIP5).

2.5. Cost Calculator

A spreadsheet model (Supplementary Materials, Tables S1–S10) 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 [30]. 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 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, labor costs, and operational costs [31], 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 labor cost was gathered from the Government of Alberta Occupations Info website [32]. 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 decomposition and planting/seedlings were required for summer logging. Decompaction and regeneration were only considered on access roads, not in the cut-blocks. 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 [33] 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 [34], and a driver should not exceed 13 h of driving time [35].

The model consists of input sections where cost was adjusted in relation to inputs and a summary panel (Supplementary Materials Table S1). 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 (Table S2), Skidding (Table S3), Delimbing (Table S4), Loading (Table S5), Hauling (Tables S6 and S7), and Road Building (Excavating) (Table S8), as well as decompaction [36], and planting/seedlings on access roads [37]. 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. [38] 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.

2.6. Hauling to the Mill Only

2.6.1. 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 [39] 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, labor cost, and operation cost.

2.6.2. 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 [40]. The ownership costs (Fc) included depreciation, insurance, and return on capital.

$$Fc = d + i + r \tag{1}$$

where

d: depreciation,
i: insurance (3.5% of equipment value) [41],
r: return on capital (10% rate of interest with annual equipment value [41],

and Depreciation (*d*) is the losses of the machine value over time until salvage value [42].

$$d = \frac{p - s}{n} \tag{2}$$

where

p: equipment purchase cost [43–48],
s: salvage value (varies from machines to machines) [49],
n: expected economic life (varies from machines to machines) [49].

Labor 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 labor 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) [42],

$$Lc = (hr_s\, w) + (hr_o\, w_o) + el \tag{3}$$

where

hr_s: seasonal (summer or winter) work hours,
w: wage [32],
hr_o: overtime worked hours. Logging industry workers are entitled to get paid overtime after 10 h of work in a day [34],

w_o: overtime wage,
el: employee load (accounts for benefits) [41].

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

$$Oc = mr + f + ol \tag{4}$$

where

mr: maintenance plus repair cost was estimated as a percentage of depreciation cost for each season [41],
f: fuel cost for each machine [50,51],
ol: oil plus lubricant cost [41].

Even though a machine was not used during the season, if it sat idle, the ownership cost was still paid. Ownership, labor 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, labor cost and operation cost.

$$Hc = \frac{Fc}{pd\ hr_a} + \frac{Lc}{pd\ hr_s} + \frac{Oc}{pd\ hr_s} \tag{5}$$

where

pd: productivity m^3 per hours,
hr_a: annual production hours,
hr_s: 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 higher numbers for the machine's needs than the longer summer.

$$Ne_{(x)} = \frac{\frac{pr_{(x)}}{de_{(x)}}}{pd_{(x)}\ hr_{(x)}} \tag{6}$$

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 at Sundays and statuary holidays subtracted from total logging days).

The hauling truck productivities (for two scenarios) and costs were calculated in a different sheet (Tables S9 and S10).

$$pd_t = \frac{c}{\frac{h_d}{s_l} + \frac{h_d}{s_u} + \frac{t_l + t_u}{60}} \tag{7}$$

where

pd_t: hauling truck productivity (m^3/hr),
c: capacity of hauling truck (m^3) [3],
h_d: hauling distance,

s_l: average speed of loaded hauling truck [39],
s_u: average speed of unloaded hauling truck [39],
t_l: loading time in minutes [45],
t_u: unloading time in minutes [45].
c: differs for non-frozen and frozen conditions, based on weight limits from Alberta transportation.

2.7. 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.

2.7.1. 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 6164 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 h of cycle time. The distance between cutblocks and the satellite yard was 40 km, with 2 h of cycle time.

2.7.2. 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 the optimum harvest volume to achieve the minimum number of hauling trucks. GRC searches a point where the slope of the objective function is zero while changing decision variables [52].

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 (N_h) possible.

The form of the objective function is as follows:

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

where

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

$$Ne_{(s)} = \frac{\frac{pr_{(s)}}{dh_{(s)}}}{pd_{t(s)}\, hr_{(s)}} \frac{1}{nt_{(s)}} \quad (9)$$

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,
$nt_{(s)}$: 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.

$$Ne_{(wm)} = \frac{\frac{pr_{(wm)}}{dh_{(wm)}}}{pd_{t(wm)}\, hr_{(wm)}} \frac{1}{nt_{(wm)}} \quad (10)$$

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.

$$Ne_{(wy)} = \frac{\frac{pr_{(wy)}}{dh_{(wy)}}}{pd_{t(wy)}\, hr_{(wy)}} \frac{1}{n_{t(wy)}} \quad (11)$$

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:

$$n_{t(x)} = \frac{hr_{(x)}}{t_{h(x)}} \quad (12)$$

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

3. Results

In the 2015–2016 logging season, we estimated 12 hauling shut-down days with a maximum temperature above 6 °C (Table 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 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.

3.1. Future Predictions

Average shut-down days between 2020 and 2039 (2030s) 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 2050s 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 2080s 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 1). These data indicate that the largest increase in shut-down days will occur in March. On the most extreme year of the 2080 period, there will be many shut-down days, even in midwinter.

3.2. Estimated Logging Cost

3.2.1. Hauling to Mill Only

The harvesting with hauling cost of the base year was 20.72 $\$/m^3$ for the summer season and 18.65 $\$/m^3$ for the winter season; the logging costs (harvesting, hauling, road building, decompaction, and planting costs) were 22.94 $\$/m^3$ for the summer season and 19.50 $\$/m^3$ for the winter season. Table 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. Unit prices for each phase of the logging operations in 2015–2016 with hauling directly to the mill.

Time	2015–2016	
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 ($/m^3)	8.20	6.11
Cost of Harvesting and Hauling ($/m^3)	20.72	18.65
Decompaction cost ($/km)	1143	0
Clearing/Piling cost ($/km)	3568	2135
Planting ($/ha)	1078	0
Total unit cost of logging ($/m^3) [1]	22.94	19.50

[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 1, the various components of logging costs were estimated for the future scenarios (Figure 2). The cost and number of idle machines are shown more clearly in Figure 3.

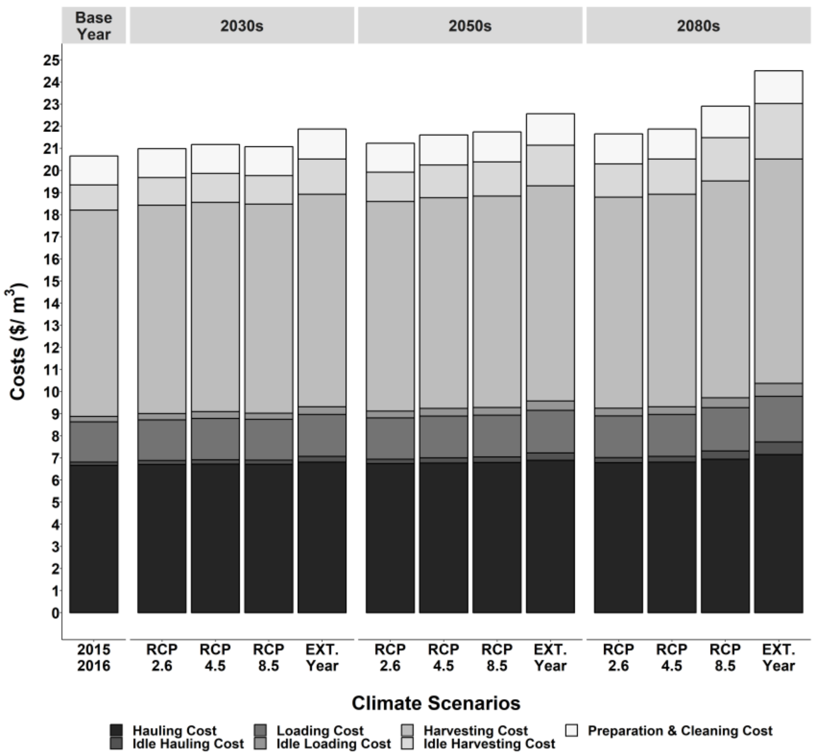

Figure 2. Total costs of logging operations (winter and summer) where the harvested wood is hauled only to the mill yard under the current climate and several future times with three different climate radiative forcing values, using the HadGEM2-ES climate model. The extreme year (EXT Year) has the warmest winter in any of the RCP values of a time interval. Calculations subtracted Sundays and holidays from time available for operations.

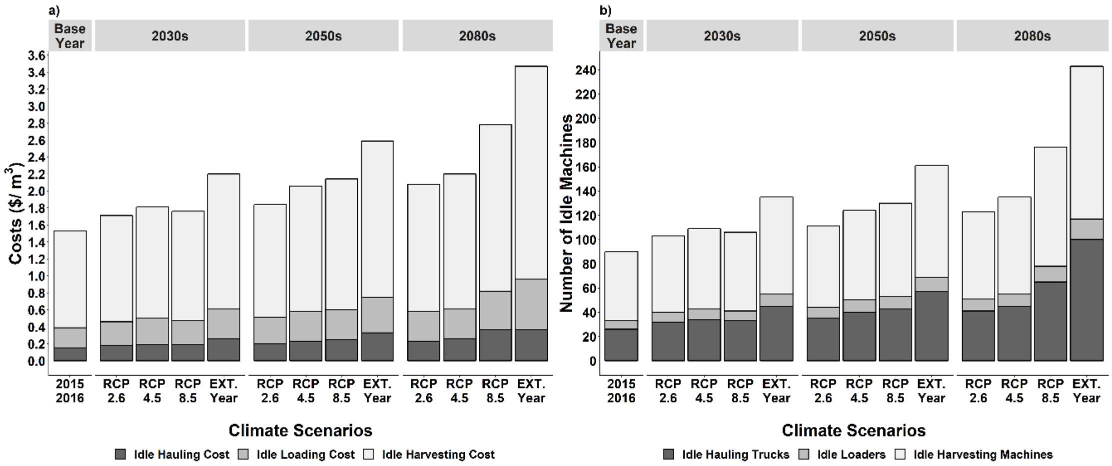

Figure 3. Analysis of idle logging equipment when logs were hauled only directly to the mill in winter, under different climate scenarios in several different times in the future; (**a**) total costs of idle machines; (**b**) total number machines that are idle in summer months. Sundays and holidays were subtracted from the available time for operations.

2030s Predictions:

In the 2030s, the total average unit logging cost ($/m^3) is expected to increase between 1.6% and 2.5% among the various scenarios compared to the base year (Figure 2), using the days available for harvesting/hauling (shut-down days, Sundays and statuary holidays subtracted from total logging days at Table 1). The main increase was from the increase in idle equipment and the costs of harvesting, loading, and hauling (Figure 3). The total idle equipment cost was 1.81 $/m^3 for the RCP 4.5, the warmest scenario for the 2030s, which was a 0.28 $/m^3 increase over the 2015–2016 idle costs. The idle hauling truck costs rose by 26.7%, 14.9% for harvesting, and 29.2% for loader costs, and there was an 18.3% increase in the total idle costs for the entire operation (Figure 3). In the extreme warmest year (of this time interval), the total logging costs will be increased by 5.9% in the 2030s and most of this was related to the need for more equipment during the shorter period of winter logging (a 43.9% increase compared to the base year), hence the high annual idle costs.

2050s Predictions:

In the 2050s, the total unit logging cost is expected to increase between 2.8% and 5.3% among the various scenarios, compared to the base year (Figure 2). The total idle equipment cost was 2.14 $/m^3 for the RCP 8.5, the warmest scenarios for 2050s, 0.61 $/m^3 more than the base year. The idle equipment costs increased by 66.7% for the hauling trucks, 35.1% for harvesting, 45.8% for the loaders, and 39.9% for the entire logging operation (Figure 3). In the extreme warmest winter of the 2050s period, the idle equipment cost was increased by 69.3% and the total logging cost increased by 9.3%.

2080s Predictions:

In the 2080s, the total unit logging cost is expected to rise between 4.8% and 10.9% among the various scenarios compared to the base year (Figure 2), using the shut-down days (Table 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 2080s was 2.78 $/m^3, which was 1.25 $/m^3 more than the base year. The idle equipment cost was 146.7% higher for trucking, 71.9% for harvesting, 87.5% for loaders, and 81.7% for the entire logging operation (Figure 3). In the extreme warmest winter of the 2080 period, the total logging cost was increased by 18.7%, and there was a 139.9% increase in idle equipment.

3.2.2. Hauling to the Mill and Satellite Yard

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 4) in warmer winters. Of the 1,400,000 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.

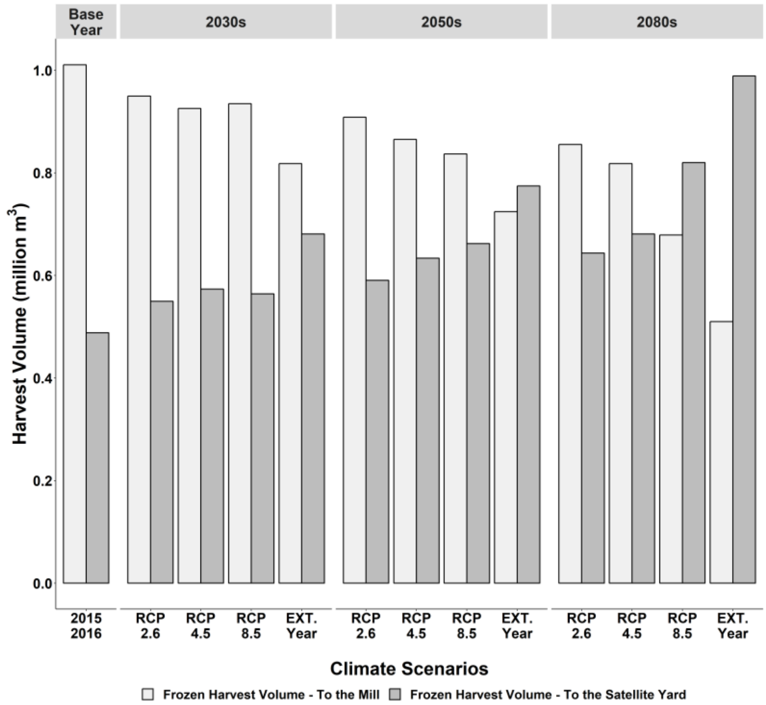

Figure 4. Use of satellite yard to distribute winter harvest volume of woods (m^3) with the criteria to minimize the total number of idle hauling trucks over the entire year under different climate scenarios at different time intervals.

2030s Predictions:

In the 2030s, the unit logging cost was expected to increase between 1.8% and 2.8% among the various scenarios compared to the base year (Figure 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 1). The main contribution to this increase was in the idle equipment costs of harvesting and loading (Figure 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 6), which was actually a warmer scenario than the RCP 8.5 for the 2030s. 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 6), which was 0.21 \$/m^3 more than the base year. The idle harvesting machine costs rose to 14.9% and 23.5% for loaders, while the idle hauling truck cost remained zero and there was a 16.0% 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 6.3% and the total idle equipment cost will increase by 39.7%.

2050s Predictions:

In the 2050s, the unit logging cost was expected to increase between 3.1% and 5.7% among the various scenarios (Figure 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 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 2050s. 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 2050s, was 1.78 \$/m^3, which was 0.47 \$/m^3 more than the base year. The idle harvesting machine costs rose to 29.8% and 41.2% for loaders, while the idle hauling truck cost remained zero (Figure 6). There was a 35.9% 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 9.8% and total idle equipment cost increased by 61.8%.

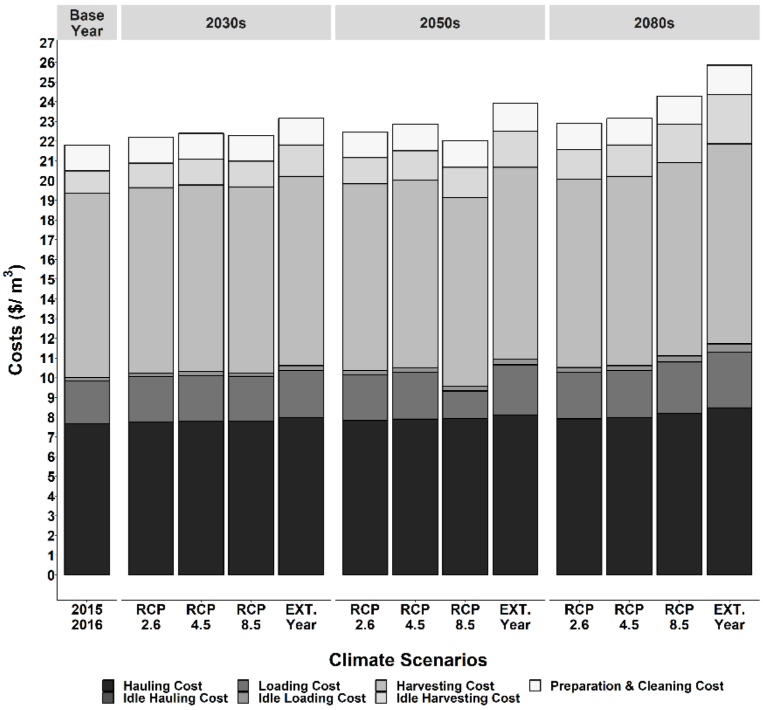

Figure 5. Total costs of logging operations (winter plus summer) where the harvested wood is hauled to both the mill and satellite yards under the current and several future intervals. The extreme year (EXT. Year) has the warmest winter in any of the RCP values of a time intervals. The normal Sundays 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 extreme warm year of the 2080s.

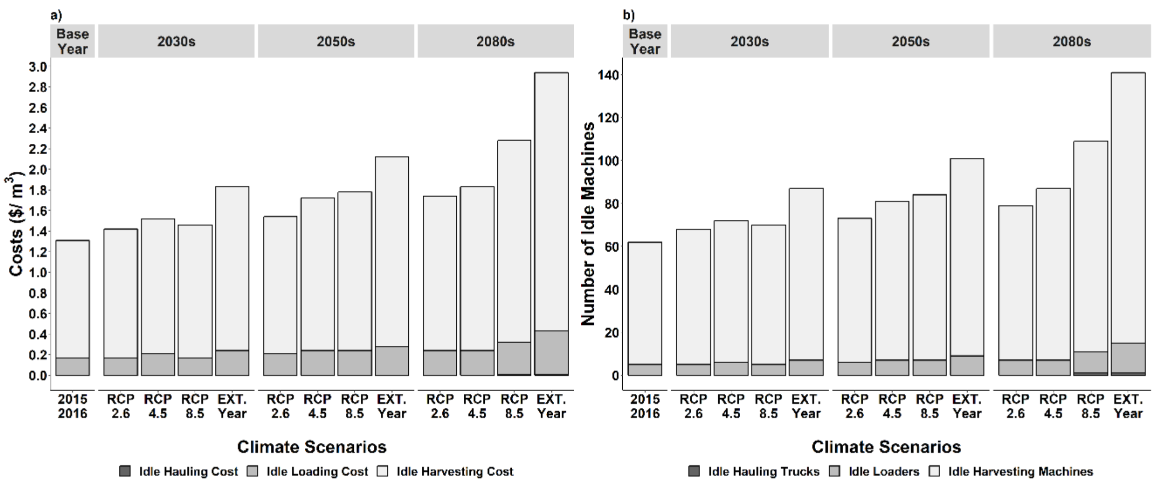

Figure 6. Analysis of idle logging equipment when logs were hauls both to the mill and satellite yards in the winter, under different climate scenarios in several different time in the future; (**a**) total unit cost of idle machines that are not operated in summer; (**b**) total number of machines that are idle in summer months. Sundays and holidays were subtracted from the available time for operations.

2080s Predictions

In the 2080s, the unit logging cost was projected to increase between 5.2% and 11.4% among the various scenarios (Figure 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 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 2080s. 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 2080 period, was 2.28 $\$/m^3$, which was 0.97 $\$/m^3$ more than the base year. The idle equipment cost was 71.9% higher for harvesting and 82.4% higher for loaders, while there was one idle hauling truck (Figure 6) and a 74.1% increase in the total idle cost for the entire operation. In the extreme warmest winter of the 2080 period, the total logging cost was increased by 18.5% and there would be a 124.4% 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 labor 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 2.5% to 1.5% for the 2030s time intervals, from 5.3% to 3.2% for the 2050s, and from 10.9% to 7.1% for the 2080s, for the analysis of hauling to the mill only. The logging cost increases compared to the base year could decline from 5.9% to 3.1% for the 2030s, 9.3% to 4.5% for 2050s, and from 18.6% to 9.1% for the 2080s 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 2.8% to 1.7% for the 2030s, from 5.7% to 3.6% for the 2050s, and from 11.4% to 7.9% for the 2080s. The logging cost increases compared to the base year declined from 6.3% to 3.7% for the 2030s, 9.8% to 5.1% for the 2050s, and from 18.5% to 9.9% for the 2080s for the extreme warm winter.

Ice roads might be particularly damaged by shutdown days that are back to back. In the extreme winter of each time period, we counted the number of times that the shutdown occurred for two or more consecutive days of the 121 eligible loggings (including Sundays and holidays). There were six shutdown intervals in the extreme year of the 2030s, eight intervals for the 2050s and 12 intervals for the 2080s.

4. Discussion

4.1. 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 5.2% to 11.4% increase in logging costs by the 2080s, 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 2080s when hauling is directly to the mill. Ownership costs of idle equipment in the summer months will increase by 81.7%, 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 139.9% in the 2080s, 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 2080s compared to hauling the mill only, but the idle truck and loading decreased by 0.50 $/m^3$ for the 2080s, 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 [53] to operate very large log trucks (up to 80,000 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.

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. 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.

4.2. Other Strategies

As our modelling results from the 2030s and 2050s 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 [54]. 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 so machines could access more in the wet areas' thawed conditions. There is a possibility that futuristic logging technologies may reduce or eliminate the soil damage that equipment and hauling trucks cause [2]. Further, building more permanent roads would help with accessibility to harvest areas [17]; 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.

4.3. The Change in The Season

The climate model indicates that March is most likely to be lost as a useful month for winter logging by the 2080s (Table 1) and companies would likely not plan for frozen conditions during this time if the 6 °C temperature was used as the threshold for shutdown. The month of February shows more shutdown 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 [55], so there is still uncertainty about the completion of road building in November.

5. Conclusions

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 2080s with the RCP 8.5 forcing factor will be up to 10.9% greater than those of today if wood is hauled directly to the mill yard and 11.4% 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.

Supplementary Materials: The following are available online at http://www.mdpi.com/1999-4907/10/5/447/s1, Table S1: Summary/Result Panel—Cost Calculator, Table S2: Cost calculation for feller buncher, Table S3: Cost calculation for skidder, Table S4: Cost calculation for delimber, Table S5: Cost calculation for loader, Table S6: Cost calculation for hauling truck (20 tons)—Hauling directly to mill, Table S7: Cost calculation for hauling truck (20tons)—Hauling directly to satellite yard, Table S8: Cost calculation for excavation to build access and in-block roads, Table S9: Hauling truck productivity—Hauling directly to mill, Table S10: Hauling truck productivity—Hauling directly to satellite yard.

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References and Notes

1. Government of Canada, N.R.C. *The State of Canada's Forests 2004–2005*; Canadian Forest Service: Ottawa, ON, Canada, 2005. Available online: https://cfs.nrcan.gc.ca/publications?id=25648 (accessed on 15 May 2018).
2. MacDonald, A.J. *Harvesting Systems and Equipment in British Columbia*; Ministry of Forests, Forest Practices Branch: Victoria, BC, Canada, 1999.
3. Government of Alberta. Log Haul Program. Available online: https://www.transportation.alberta.ca/3193.htm (accessed on 15 February 2018).
4. Spittlehouse, D.L. Integrating Climate Change Adaptation into Forest Management. *For. Chron.* **2005**, *81*, 691–695. [CrossRef]
5. Geisler, E.; Rittenhouse, C.D.; Rissman, A.R. Logger Perceptions of Seasonal Environmental Challenges Facing Timber Operations in the Upper Midwest, USA. *Soc. Nat. Resour. Phila.* **2016**, *29*, 540–555. [CrossRef]
6. Government of Alberta. Alberta Agriculture and Forestry Impact of Forest Harvest. Available online: https://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/apa3317 (accessed on 12 May 2018).
7. Frey, B.R.; Lieffers, V.J.; Landhausser, S.M.; Comeau, P.G.; Greenway, K.J. An Analysis of Sucker Regeneration of Trembling Aspen. *Can. J. For. Res.* **2003**, *33*, 1169–1179. [CrossRef]
8. Johnston, M. *Impact of Climate Change on Forest Productivity in Mistik FMA Area*; Mist. Manag. Ltd.: Saskatoon, SK, Canada, 2007.

9. Aust, W.M.; Blinn, C.R. Forestry Best Management Practices for Timber Harvesting and Site Preparation in the Eastern United States: An Overview of Water Quality and Productivity Research during the Past 20 Years (1982–2002). *Water Air Soil Pollut. Focus* **2004**, *4*, 5–36. [CrossRef]
10. Kienzle, S. Alberta Climate Records. Available online: http://albertaclimaterecords.com/ (accessed on 9 January 2018).
11. Wang, T.; Hamann, A.; Spittlehouse, D.; Carroll, C. Locally Downscaled and Spatially Customizable Climate Data for Historical and Future Periods for North America. *PLoS ONE* **2016**, *11*, e0156720. [CrossRef] [PubMed]
12. Semenov, M.; Barrow. Lars-WG–A Stochastic Weather Generator for Use in Climate Impact Studies. User Manual Herts UK. 2002. Available online: https://sites.google.com/view/lars-wg (accessed on 2 February 2018).
13. Thornton, P.E.; Thornton, M.M.; Mayer, B.W.; Wei, Y.; Devarakonda, R.; Vose, R.S.; Cook, R. *Daymet: Daily Surface Weather on a 1 Km Grid for North America, 1980–2008*; Oak Ridge National Laboratory (ORNL) Distributed Active Archive Center for Biogeochemical Dynamics (DAAC): Oak Ridge, TN, USA, 2012.
14. British Columbia Ministry of Forests. *Riparian Management Area Guidebook*; ProQuest Micromedia: Victoria, BC, Canada, 1995.
15. Rittenhouse, C.D.; Rissman, A.R. Changes in Winter Conditions Impact Forest Management in North Temperate Forests. *J. Environ. Manag.* **2015**, *149*, 157–167. [CrossRef] [PubMed]
16. Barrow, E.; Maxwell, B.; Gachon, P. *Climate Variability and Change in Canada. Past, Present and Future*; ACSD: Meteorological Service of Canada, Environment Canada: Toronto, ON, Canada, 2004.
17. Johnston, M.H.; Williamson, T.B.; Munson, A.D.; Ogden, A.E.; Moroni, M.T.; Parsons, R.; Price, D.T.; Stadt, J.J. *Climate Change and Forest Management in Canada: Impacts, Adaptive Capacity and Adaptation Options*; A State of Knowledge Report: Edmonton, AB, Canada, 2010.
18. Government of Alberta. Offsite Timber Storage Sites; Agriculture and Forestry, Forest Management Branch. 2016. Available online: https://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/formain15847/$FILE/offsite-timber-storage-directive-2016-01.pdf (accessed on 20 November 2018).
19. Lemmen, D.S.; Warren, F.J.; Lacroix, J.; Bush, E. *From Impact to Adaptation: Canada in a Changing Climate 2007*; Government of Canada: Ottawa, ON, Canada, 2008; p. 448.
20. Williamson, T.B.; Colomba, S.J.; Duinker, P.N.; Gray, P.A.; Hennessey, R.J.; Houle, D.; Johnston, M.H.; Ogden, A.E.; Spittlehouse, D.L. *Climate Change and Canada's Forests: From Impacts to Adaptation.; Sustainable Forest Management Network and Natural Resource Canada*; Canadian Forest Service, Northern Forest Centre: Edmonton, AB, Canada, 2009; p. 104.
21. Kestler, M.A.; Knight, T.; Krat, A.S. *Thaw Weakening and Load Restriction Practices on Low Volume Roads.; ERDC/CRREL TR-00-6*; US Army Corps of Engineers, COLD REGIONS RESEARCH AND ENGINEERING LAB: Hanover, NH, USA, 2000.
22. Chan, T.; Cordeau, J.-F.; Laporte, G. Locating Satellite Yards in Forestry Operations. *INFOR Ott.* **2009**, *47*, 223–234. [CrossRef]
23. Rogelj, J.; Meinshausen, M.; Knutti, R. Global Warming under Old and New Scenarios Using IPCC Climate Sensitivity Range Estimates. *Nat. Clim. Chang.* **2012**, *2*, 248–253. [CrossRef]
24. Van Vuuren, D.P.; Stehfest, E.; den Elzen, M.G.J.; Kram, T.; van Vliet, J.; Deetman, S.; Isaac, M.; Klein Goldewijk, K.; Hof, A.; Mendoza Beltran, A.; et al. RCP2.6: Exploring the Possibility to Keep Global Mean Temperature Increase below 2°C. *Clim. Chang.* **2011**, *109*, 95. [CrossRef]
25. Thomson, A.M.; Calvin, K.V.; Smith, S.J.; Kyle, G.P.; Volke, A.; Patel, P.; Delgado-Arias, S.; Bond-Lamberty, B.; Wise, M.A.; Clarke, L.E.; et al. RCP4.5: A Pathway for Stabilization of Radiative Forcing by 2100. *Clim. Chang.* **2011**, *109*, 77–94. [CrossRef]
26. Van Vuuren, D.P.; Edmonds, J.; Kainuma, M.; Riahi, K.; Thomson, A.; Hibbard, K.; Hurtt, G.C.; Kram, T.; Krey, V.; Lamarque, J.-F.; et al. The Representative Concentration Pathways: An Overview. *Clim. Chang.* **2011**, *109*, 5. [CrossRef]
27. Sheffield, J.; Barrett, A.P.; Colle, B.; Fernando, N.; Fu, R.; Geil, K.L.; Hu, Q.; Kinter, J.; Kumar, S.; Langenbrunner, B.; et al. North American Climate in CMIP5 Experiments. Part I: Evaluation of Historical Simulations of Continental and Regional Climatology. *J. Clim.* **2013**, *26*, 9209–9245. [CrossRef]

28. Sheffield, J.; Camargo, S.J.; Johnson, N.; Jiang, X.; Fu, R.; Karnauskas, K.B.; Hu, Q.; Kinter, J.; Kumar, S.; Langenbrunner, B.; et al. North American Climate in CMIP5 Experiments. Part II: Evaluation of Historical Simulations of Intraseasonal to Decadal Variability. *J. Clim.* **2013**, *26*, 9247–9290. [CrossRef]
29. Racsko, P.; Szeidl, L.; Semenov, M. A Serial Approach to Local Stochastic Weather Models. *Ecol. Model.* **1991**, *57*, 27–41. [CrossRef]
30. Tufts, R.A.; Lanford, B.L.; Greene, W.D.; Burrows, J.O. Auburn Harvesting Analyzer. *Compiler* **1985**, *3*, 14–15.
31. Brandstrom, A.J.F. *Analysis of Logging Costs and Operating Methods in the Douglas Fir Region*; West Coast Lumbermen's Association: Northwest Forest Experimental Station, Forest Service, United States Department of Agriculture: Portland, OR, USA, 1933.
32. Logging Machinery Operators: Wages and Salaries in Alberta-alis. Available online: https://alis.alberta.ca/occinfo/wages-and-salaries-in-alberta/logging-machinery-operators/8241/ (accessed on 18 December 2015).
33. OCCIAR. *Climate Change Impacts and Adaptation in Northern Ontario—Workshop Report*; Ontario Centre for Climate Impacts and Adaptation Resources: Sudbury, ON, Canada, 2011.
34. Government of Alberta. Employment Standards Regulation; Alberta Regulation 14/1997. 2018; p. 72. Available online: http://www.qp.alberta.ca/documents/Regs/1997_014.pdf (accessed on 4 February 2019).
35. Government of Alberta. Drivers' Hours of Service Regulation; Alberta Regulation 317/2002. 2017; p. 20. Available online: http://www.qp.alberta.ca/documents/Regs/2002_317.pdf (accessed on 4 February 2019).
36. Sessions, J.; Sessions, J.B. *Cost Control in Forest Harvesting and Road Construction*; Food and Agriculture Organization of the United Nations: Rome, Italy, 1992.
37. USDA. Temporary Road Cost Estimating. In *Cost Estimating Guide for Road Construction*; USDA Forest Service Northern Region: Portland, OR, USA, 2017.
38. Kuhnke, D.H.; Bohning, R.A.; White, W.A. *The Alberta Logging Cost Survey: Data for 1996-98*; Canadian Forest Service: Edmonton, AB, Canada, 2002; 74p.
39. Sergei Dratchev. Episode 22: Trucking with Sergie Dratchev; 2013.
40. Bushman, S.P.; Olsen, E.D. *Determining Costs of Logging-Crew Labor and Equipment*; Forest Research Lab, College of Forestry, Oregon State University: Oakridge, OR, USA, 1988.
41. Boerner, D. *Forestry Handbook*, 2nd ed.; Wenger, K.F., Ed.; Society of American Foresters, John Wiley & Sons: New York, NY, USA, 1984; Volume 90, p. 57.
42. Miyata, E.S. *Determining Fixed and Operating Costs of Logging Equipment*; North Central Forest Experiment Station, Forest Service, U.S. Dept. of Agriculture: St. Paul, MN, USA, 1980.
43. 2013 John Deere 753J-Forestry Feller Bunchers. Available online: https://www.machinefinder.com/ww/en-US/machines/2013-john-deere-753j-feller-buncher-6094805 (accessed on 21 February 2019).
44. 2014 John Deere 648H-Forestry Skidders. Available online: https://www.machinefinder.com/ww/en-US/machines/2014-john-deere-648h-skidder-5859561 (accessed on 21 February 2019).
45. 2013 John Deere 2154D-Forestry Delimbers. Available online: https://www.machinefinder.com/ww/en-US/machines/2013-john-deere-2154d-tree-delimber-6184982 (accessed on 21 February 2019).
46. 324D FM. Available online: https://www.finning.com/en_CA/products/new/equipment/forest-machines/forest-machines/17532207.html (accessed on 21 February 2019).
47. 2015 John Deere 470GL-Excavators. Available online: https://www.machinefinder.com/ww/en-US/machines/2015-john-deere-470gl-excavator-6036024 (accessed on 21 February 2019).
48. 2011 FREIGHTLINER 122SD For Sale In West Kelowna, British Columbia Canada. Available online: https://www.truckpaper.com/listings/trucks/for-sale/30645639/2011-freightliner-122sd (accessed on 21 February 2019).
49. Akay, A.E. Estimating Machine Rates and Production for Selected Forest Harvesting Machines Operating in the Western United States and Determining the Most Economical Machine Combinations under Representative Conditions in Turkey. Maste's Thesis, Oregon State University, Corvallis, OR, USA, 15 January 1998.
50. Smidth, M.; Gallagher, T. *Factors Affecting Fuel Consumption and Harvesting Costs. Forest Operations for a Changing Landscape*; Council on Forest Engineering: Missoula, MT, USA, 2013.
51. Kenny, J. Factors That Affect Fuel Consumption and Harvesting Cost. Master's Thesis, Auburn University, Auburn, AL, USA, 13 May 2015.
52. Winston, W.L. *Microsoft Excel 2010 Data Analysis and Business Modeling*, 3rd ed.; Microsoft Press: Redmond, WA, USA, 2011.

53. Mitchell, D.L.; Gallagher, T.V.; Thomas, R.E. The Human Factors of Implementing Shift Work in Logging Operations. *J. Agric. Saf. Health* **2008**, *14*, 391–404. [CrossRef] [PubMed]
54. Johnston, M.H.; Williamson, T.B.; Wheaton, E.E.; Wittrock, V.; Nelson, H.; Hesseln, H.; Vandamme, L.; Pittman, J.; Lebel, M. *Climate Change Adaptive Capacity of Forestry Stakeholders in the Boreal Plains Ecozone*; Canadian Forest Service: Edmonton, AB, Canada, 2008.
55. Bradley, A.H.; Thiam, P. Development and Validation of a Freezing Pavement Analysis to Refine Alberta's Winter Weight Policy. In *TAC 2018: Innovations in Pavement Management, Engineering and Technologies—Conference of the Transportation Association of Canada Saskatoon, Saskatoon, SK, Canada, 25 October 2018*; Transportation Association of Canada (TAC): Ottawa, ON, Canada, 2018.