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Partial Harvest in Paludified Black Spruce Stand: Short-Term Effects on Water Table and Variation in Stem Diameter

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Abstract: The boreal forest is considered to be a low productivity forest due to its cold climate and poorly drained soils promoting paludification. These factors create conditions favouring accumulation of undecomposed organic matter, which causes declining growth rates of forest stands, ultimately converting mature stands into peatlands. Under these conditions, careful logging is conducted during winter, which minimizes soil disturbance in northwestern Quebec boreal forest. This results in water table rise, increased light availability and paludification. Our main objective was to evaluate the short-term effect of partial harvesting as an alternative method to careful logging in winter to mitigate water table rise on black spruce (*Picea mariana* [Mill.] B.S.P.) stands. We quantified tree stem diameter variation and daily variation in water table depth in mature spruce stands before and after partial harvest (basal area reduction of 40%) and girdling (same basal area reduction with delayed mortality) during 2016 and 2017 growing seasons. Water table variation prior to and following silvicultural treatments did not differ one year after treatment. Daily stem diameter variation in black spruce did not differ between treatments and control. Furthermore, temperature exerted a positive effect on variation in water table and on stem diameter. These results suggest that partial harvest could be more effective than clearcutting to mitigate negative effects of a high water table while limiting paludification.

Keywords: boreal forest hydrology; forest management; black spruce-feather moss domain; paludification; partial harvest; water table level

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1. Introduction

Forestry practices in the boreal forest of Canada have focused principally on ecosystem management to meet the objectives of sustainable forest management that are set by its federal and provincial governments [1,2]. Managing forests using this approach would preserve biological diversity and maintain ecological functions of the ecosystem [3,4]. Consistent with this concept of ecosystem management, Lecomte et al. [5] highlighted the importance of forest structure and its effects on forest dynamics. Structural diversity is a key feature that must be reproduced in managed forests to maintain biodiversity and essential ecological functions [3]. One should focus on creating irregular structure to maintain the same percentage of even- and uneven-aged stands as a forest landscape under natural disturbance regimes [6]. To balance ecological integrity and timber production in extensively managed boreal forests, the best option would typically combine partial harvests and clearcuts [7]. Currently, the Canadian boreal forest is largely managed with even-aged harvesting such as clear cutting and its variants (>95% of the area harvested annually), whereas uneven-aged management consisting of partial harvest is marginal (<5% of the area harvested annually) [8]. In this article, the term partial harvesting refers to various forms of shelterwood and thinning intensities that seek to create structural diversity emulating the structures generated by natural disturbances, such as windthrow and insect outbreaks [1,9]. Specifically, partial harvest can also be considered as variable density thinning, a silvicultural strategy developed to quickly reach the structure of a late-successional habitat [10]. At low intensities, partial harvest treatments can retain a continuous cover forestry [11].

Black spruce (*Picea mariana* [Mill.] B.S.P.) stands on thick organic soils are common in the North American boreal forest. In this ecosystem, paludification is a main driver of stand structure in the absence of wildfire [5]. Paludification is commonly described as the accumulation of an organic layer on a mineral soil mainly through sphagnum moss (*Sphagnum* spp.) growth [12]. Thick sphagnum layers create a perched water table on top of mineral soil, which is isolated from regional groundwater sources [13]. Flat topography increases paludification rates and decreases stand productivity [14]. Simard et al. [15] demonstrated declines in stand productivity ranging from 50 to 80% in heavily paludified stands. Time-since-fire is the main factor influencing forest floor thickness, followed by fire severity [16,17].

Partial harvesting comes with the risk of losing residual trees following treatment. This risk is modulated by topography, the quantity of saplings, percentage removal of basal area, soil type, and distance from skid trails [18,19]. In black spruce stands on organic soils, the risk of losing residual trees is mostly due to proximity to skid trails which cause windthrow and dead standing trees [18]. In this stand type, we posit that an additional problem is water table rise following harvest, which can induce tree mortality [20,21]. Over longer periods following harvest, the water table can rise further in the absence of fire when sphagnum growth increases with the formation of canopy openings [17,22]. On thick organic soils, the perched water table rises between 2.6 and 22 cm following silvicultural treatments, such as clearcutting and pre-commercial thinning [23–26]. Furthermore, mean water table rises after silvicultural treatments is greater on sites with thin organic layers than on sites with thick organic layers [23,25]. Soil texture also influences the rise of the water table, with higher water tables on fine-textured soils [23,25]. Dubé et al. [23] had identified interception as the key factor for watering-up after careful logging during winter. The reduction of stem density following logging is also an important stand characteristic for rain interception in balsam fir (*Abies balsamea* [L.]. Mill.) stands [27]. Yet, Jutras et al. [26] suggested that the main hydrological process influencing water table depth was the reduction of evaporation and transpiration following pre-commercial thinning. They further suggested that light to moderate pre-commercial thinning would reduce water table rise when compared to heavy thinning. Similarly, Pothier et al. [28] proposed light partial harvesting as a means of mitigating water table rise. According to the literature, the reduction of interception has a greater impact on water table depth than evaporation and transpiration after logging on organic soils. Testing the effects of partial harvesting on the water table is crucial for understanding hydrological processes that occur following treatment.

It is difficult to investigate the effect of silvicultural treatments on tree growth over the course of a short-term study. Yet, monitoring variation in stem diameter on a daily basis can reveal rapid responses to environmental change [29], such as those that are induced by silvicultural harvesting (rapid changes in evapotranspiration and temperature). Therefore, studying stem diameter variations is relevant even in short-term study. Stem diameter variations originate from turgidity (diurnal variation due to water storage) [30] and wood production during tree growth [31–33]. Slow-growing trees such as black spruce have more diameter variation that is due to water uptake than it is due to wood production [29]. Furthermore, black spruce turgidity is thought to be mainly affected by temperature, soil moisture content, and precipitation [29].

The objectives of this study were two-fold: (*1*) to quantify the daily variation in water table depth following partial harvesting and girdling treatments in black spruce stands; and (*2)* to measure the influence of environmental conditions and water table variation due to partial harvesting and girdling treatments on daily variation in black spruce stem diameter. We hypothesized that (*i*) comparisons of partial harvesting and girdling treatments can isolate the effect of interception on daily variation in water table depth; (*ii)* the most important factor explaining daily variation in water table depth is the reduction in interception one year after silvicultural treatment, as observed by Plamondon et al. [27] and Dubé et al. [23]; (*iii*) changes in transpiration that are induced by silvicultural treatments have negligible effects on daily variation in water table depthfor the duration of our study, as observed by Plamondon et al. [27] and Dubé and Plamondon [34]; (*iv*) the daily variation in water table influences black spruce stem diameter, which is an indicator of diameter growth and turgidity [29,32].

2. Materials and Methods

2.1. Study Area

The study took place in the Clay Belt of northwestern boreal Quebec, within the black spruce-feather moss bioclimatic domain (Figure 1) [35]. The thick clay soil was deposited during the Wisconsin period by proglacial Lake Ojibway [36]. In Abitibi, the fire cycle was estimated to be 135 years between 1850 and 1920. From 1920 until the present, the fire cycle is estimated to exceed 400 years [37]. Rapid change in fire cycle length is mainly due to fire suppression and climate change [38,39]. Study sites were located at 49°33′ N, 78°58′ W, 50 km north of Villebois (Figure 1). Mean annual temperature is 0.0 °C, average precipitation is 909 mm, and mean growing degree-days are 1200 to 1400 at the weather station closest to the study sites [40]. Clay soils, flat topography, and a cold and humid climate make soils in the region vulnerable to paludification [17].

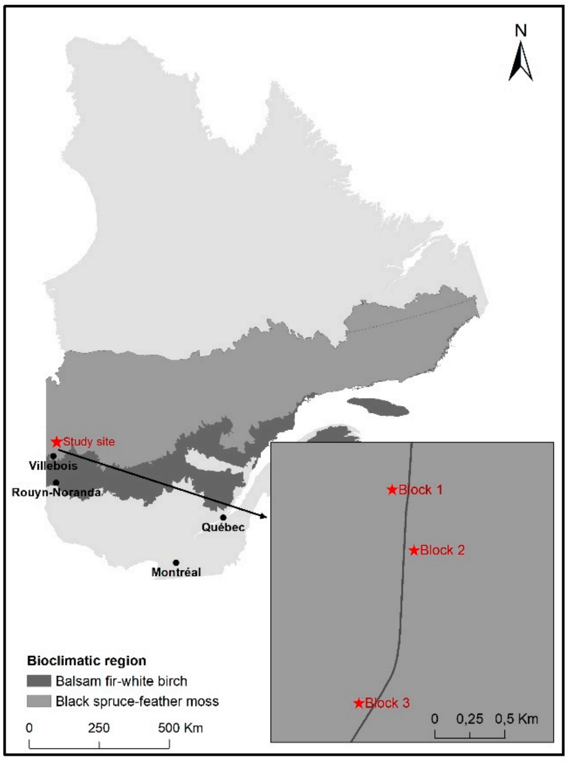

Figure 1. Location of the experimental plots. Each block contains one plot of each 3 treatments (control, girdling and partial harvest).

All data were collected in old-growth black spruce stands (between 150 and 180 years of age) during the growing seasons (May to September) of 2016 and 2017. We established three randomized blocks in which each of three treatments were applied: partial harvest, girdling, and control plots. Girdling consisted of stripping the stem bark to the xylem at breast height, subsequently stopping sap flow and transpiration while keeping the same interception for about 2 years [41]. Thus, comparing partial harvest and girdling treatments should allow separation of the effects of transpiration and interception on water table variation. Partial harvest removed about 40% of merchantable basal area (9 cm $\geq$ DBH), focusing on larger DBH trees and was conducted with chainsaws (Table 1). This means there was no soil disturbance associated with the partial harvest, as the aim of the study was the short-term effect on the treatment on the water table. Girdling was also applied on about 40% of merchantable basal area, focusing on larger DBH trees (Table 1). It was performed with hand saws removing a 20-cm strip of bark and wood from the stem. The strip was approximately 3 cm deep and was scrubbed with a metal brush to stop sap flow. We placed two dendrometers on six different trees to ensure the efficiency of the girdling treatment. There were no radial variation on the girdled trees. Partial harvest and girdling were performed on 7 July 2016 and were applied to a 900 m^2 (30 m $\times$ 30 m) plot, although data were only collected in the centremost 400 m^2 (20 m $\times$ 20 m). We applied the treatments on a larger surface area to increase chances of observing hydrological effects on water table depth and black spruce stem diameter variation. Plots were separated by at least 70 m from one another and from roads to minimize hydrological effects of these manipulations. The three blocks were situated within 1.5 km of a forestry road. We implemented a before-after control-impact (BACI) experimental design, where the period before treatment was from 9 June 2016 to 6 July 2016, while the period following treatment application was from 7 July 2016 to 21 August 2017. We did not analysed the data during winter or during the water table was frozen. During these periods, daily water table depth was measured. Merchantable basal area in the plots ranged from 6.6 to 23.4 m^2 ha^{-1}, while mean organic matter thickness was about 60 cm (Table 1). We mapped each plot (400 m^2) to locate trees with stem diameters greater than 9 cm DBH. Mapping allowed us to extrapolate the number of stems to a hectare basis and to precisely determine basal area (Table 1). Understory vegetation consisted of shrubs in the family Ericaceae, viz., *Rhododendron groenlandicum* (Oeder) Kron & Judd, *Kalmia angustifolia* L. and blueberry species (*Vaccinium angustifolium* Aiton and *Vaccinium myrtilloides* Michaux).

Table 1. Merchantable basal area and the number of stems ha^{-1} (mean $\pm$ SD) per plot, before and after application of treatments, together with mean organic matter depth.

	Partial Harvest	**Girdling**	**Control**
Number of plots per treatment	3	3	3
Canopy openness before treatment (%)	33.7 ± 5.2	34.8 ± 6.8	27.8 ± 7.2
Canopy openness after treatment (%)	34.4 ± 5	34.9 ± 6.3	27.7 ± 7.0
Basal area before treatment (m^2/ha)	16.1 ± 6.7	14.8 ± 8.0	15.6 ± 7.8
Basal area after treatment (m^2/ha)	10.1 ± 4.1	8.8 ± 4.7	15.6 ± 7.8
Proportion of affected basal area (%)	37.1 ± 0.7	40.7 ± 1.8	0
Stems ha^{-1} before treatment	2408 ± 181	1891 ± 440	2125 ± 328
Stems ha^{-1}after treatment	2192 ± 231	1891 ± 440	2125 ± 328
Mean organic matter depth (cm)	59.3 ± 16.4	61.3 ± 20.2	52.3 ± 13.3

Note: Average organic depths and canopy openness were estimated from five measurements per plot.

2.2. Data Collection

Each plot was equipped with a water well, which was located in its center, and constructed from PVC tubing 4 cm in diameter and 1.22 m long. We perforated the portion of the tube to be inserted into the organic soil. Tubes were inserted in the organic matter down to the clay layer in a hole excavated with a manual soil auger. The wells were covered with nylon socks before their insertion in the soil to prevent obstruction of the holes by the peat. The auger was used to measure organic matter depth throughout the plot at 9 different locations. Each well was equipped with an automatic water table sensor (Dataflow Systems Ltd, Odyssey© water level loggers 1 m-long, precision ± 0.8 mm, New Zealand) that collected water table depths hourly during the 2016 and 2017 growing seasons. Daily depth differences were originally from midnight to midnight. However, we shifted the daily depth differences to the period of 8:00 to 8:00 to follow tree turgidity that peaks around 8:00 every day.

During the 2017 growing season, 45 black spruce (five per plot) were monitored with dendrometer bands to obtain their daily diameter variations. Variations in black spruce stem diameter were the proxy that was selected which is composed of tree turgidity, and growth [29]. We expected stem diameter would respond rapidly to treatment even one year after the treatments [29]. We selected mature trees that appeared vigorous based on foliage, absence of scars, and general condition. These criteria were consistent with Braido dos Santos [42], who showed that black spruce under 35 years of cambial age was more likely to react positively, with growth gains after partial harvest. Automatic dendrometers (Ecomatik Radius dendrometer DR©, Munich, Germany) monitored stem diameter and were wired to data loggers (Delta-T Devices, GP2 data loggers© Advanced data loggers, Cambridge, United Kingdom). Dendrometers were mounted at DBH (1.3 m) and were oriented north to minimize the solar radiation on the equipment and, to avoid spurious measurements.

Canopy openness was measured before and after the silvicultural treatments during the same period in 2016 and 2017 with 5 hemispheric photographs per plot: one in the centre and four in a square formation aligned with the cardinal directions 5 m from the centre. All pictures were taken on each plot within a one-hour interval before and after sunrise to minimize light intensity variation (i.e., 4:00–6:00). The camera was mounted on a tripod with a self-balance system to follow the microtopography. The pictures were analyzed with WinSCANOPY© software (Regent instruments inc, Quebec City, Canada) to extract the canopy openness percentage before and after treatment. Plots were classified into three categories for the analysis: low canopy openness = 21% (smallest opening that was encountered); medium = 32% (average opening encountered); and high = 43% (highest opening encountered). Temperature (°C) and precipitation (mm/day) that were used in analysis were retrieved from the closest weather station in Joutel (<50 km distance).

Vegetation around each well was characterized with circular plots 1.4 m-radius. A total of nine circular plots were sampled per plot (20 m × 20 m), corresponding to the surface surrounding each water wells. Percent cover was divided into the following categories: present but < 1%; 1–15%; 15–25%; 25–50%; 50–75%; and > 75%. Each species was then divided into three categories, based upon Fenton and Bergeron [43]: mosses and lichens; hummock sphagna; and plateau sphagna (Table 2). At the time of the identification of sphagna species the article of Hassel et al. [44] was not published. This is why sphagna identified as *S. magellanicum* will be referred as either *S. divinum* or *S. medium* (Table 2). These categories identified the dominant bryophyte group per plot and the ones that would have a greater effect upon water table depth and variation in black spruce stem diameter which are hummock sphagna. We used percentage cover throughout each plot to predict variation in stem diameter due to the root system being spread all over plots.

Table 2. Subdivision of bryophytes in three categories: mosses and lichens, hummock sphagna, and plateau sphagna.

Mosses and Lichens	Hummock Sphagna	Plateau Sphagna
Pleurozium schreberi	*Sphagnum capillifolium*	*Sphagnum wulfianum*
Ptilidium ciliare	*Sphagnum russowii*	*Sphagnum angustifolium*
Ptilium crista-castrensis	*Sphagnum fuscum*	*Sphagnum divinum or Sphagnum medium*
Hylocomium splendens		
Cladonia rangiferina		
Cladonia stellaris		

2.3. Statistical Analysis

2.3.1. Analysis of Water Table

The response variable used for the analysis was daily variation in water table depth (ΔWT):

$$\Delta WT = WTD_{dayx} - WTD_{dayx\text{-}1}, \tag{1}$$

We use daily variation in water table depth to facilitate comparisons among the different sampling plots and to easily isolate all the hydrological effect (interception, transpiration and evaporation). Furthermore, changes in ΔWT is also more important in a short-term study where large changes in water table depth are unlikely to happen during a short period of time. Variations in water table depth (ΔWT) and daily mean stem diameter in block i in treatment j on day k were analyzed with linear mixed models [45], with the basic formulation:

$$\Delta WT_{ijk} = \alpha_i + \gamma_j \sum_{\alpha=0}^{m} \beta_\alpha X_i + Ie_{ijk}, \tag{2}$$

where α_i ~N(μ_{Block}, σ_{Block}) are normally-distributed random intercepts associated with each block, where γ_{j} ~ N(0, $\sigma_{\mathrm{Treatment:Block}}$) are normally-distributed deviations of treatment nested within block, and where β is a vector of m fixed effects such as treatment or precipitation. The final term, ε_{ijk} ~ N(0, $\sigma_{\mathrm{residual}}$) corresponds to normally-distributed errors. We included the blocks and treatments nested within blocks as random factors. To account for the temporal autocorrelation among successive observations, we incorporated a continuous first-order autoregressive correlation structure into the model. We analyzed the data separately between periods (before and after silvicultural treatments). We used ΔWT as the response variable in our hydrological model rather than water table depth to give us the chance to detect any effect considering the length of our study. Furthermore, it allows us to detect the effect of interception during rain events and transpiration during drought by comparing the treatments.

We lagged precipitation by one day to account for the delay in water penetrating into the soil and reaching the perched water table. A square-root transformation was applied on ΔWT.

We formulated nine candidate models, based upon stand characteristics and silvicultural treatments (Table 3). The explanatory variables were divided in those based upon stand characteristics and those based upon silvicultural treatments. This division differentiated the effect of harvesting over the baseline effect of the unharvested plot on ΔWT. Some variables were shared by both categories, since silvicultural treatments could change with time their effect on ΔWT (Table 3). Furthermore, climatic variables such as temperature and precipitation included in both categories since the focus of the study was not on these climatic variables. Although we did not have throughfall measurements on each plot, we used two interactions to detect the effect of throughfall on ΔWT (precipitation$\times$canopy openness and precipitation x silvicultural treatments) (Table 3). We compared candidate models using model selection based upon the second-order Akaike information criterion (AIC_c) [46]. Model parameters were estimated using maximum likelihood in R using the *nlme* package [47,48]. We checked normality of residuals and homoskedasticity to ensure assumptions of the model were met. For each explanatory variable, the confidence level was set at 95%, and confidence intervals excluding 0 indicated that the response variable varied with a given explanatory variable [49]. The global model and a null model were included to test the null hypothesis that none of the variables influenced the response variable. An estimate of the predictive power (marginal R^2) of all candidate models was obtained with the *MuMin* package [50,51].

Table 3. List of candidate models explaining daily variation of water table depth between consecutive days (Δ*WT*) before and after treatments in 2016 and 2017, during the growing season (May to September). Each model type is based upon either stand characteristics or silvicultural treatment effects. Candidate variables included temperature (TEMP), canopy openness (CANOP), standardized precipitation that was lagged by one day (PRECL), stem ha^{-1} (STEM), silvicultural treatments (TREAT) with three different levels (control, partial harvest, girdling), basal area (BASAL), and water table depths (WTD). The third column is the expected effect on Δ*WT*, the hypotheses tested and the associated references.

Model Type	Candidate Models	Expected Effect and Hypotheses Tested
Stand characteristics models	ΔWT ~ STEM + PRECL + TEMP + CANOP	Negative effect of high stem density and high temperature. Positive effect of precipitation and greater canopy openness [27].
	ΔWT ~ PRECL + TEMP + CANOP +CANOP: TEMP	Interaction between temperature and canopy openness. Positive effect of precipitation [43].
	ΔWT ~ TEMP+ PRECL+CANOP+ PRECL: CANOP	Negative effect of high temperature. Interaction between precipitation and canopy openness [43].
	ΔWT ~ TEMP + PRECL+ CANOP +STEM+ CANOP: PRECL +CANOP: TEMP	Most complex stand characteristics model.
Silvicultural models	ΔWT ~ TREAT + PRECL + WTD	Positive effect of precipitation. Differences among treatments [23,24,26,52]. H1, H2, H3
	ΔWT ~ WTD + PRECL + WTD: PRECL	Different effect of precipitation following water table depth [23,24,26,52].
	ΔWT ~ BASAL + TREAT + BASAL: TREAT	Different effect among treatments following basal area [23,24,26,52]. H1, H2, H3
	ΔWT ~ WTD + TREAT + PRECL TREAT: PRECL	Effect of the water table depth. Different effect of precipitation among treatments [23,24,26,52]. H1, H2, H3
	ΔWT ~ WTD + TREAT + PRECL + BASAL + TREAT: PRECL + TREAT: BASAL + WTD: PRECL	Most complex silvicultural model.
ΔWT ~ 1		Null model.

2.3.2. Analysis of Stem Diameter Variation

For the analysis of stem diameter variation, we used an approach that was similar to Tardif et al. [31], where they averaged hourly measurement of stem diameter into daily mean stem diameter as the response variable. This eliminates the effect of diurnal temperature and moisture changes on stem circumference [31]. We applied a logarithmic transformation to daily mean stem diameter variation to meet the assumptions of homoskedasticity and normality of residuals. We used daily mean stem diameter in the 45 black spruce as a response variable in our models. Initially, we included block and treatment nested in the block as random effects. Yet, variation that was associated with the treatment nested within block was very small and introduced instability into the model. Instead, we included a random effect for each individual tree. Variation in stem diameter was temporally autocorrelated. Therefore, we added a continuous first-order correlation structure as previously mentioned for the models of ΔWT. Ten models were considered, divided into two model types: silvicultural and stand characteristics (Table 4). Silvicultural models consisted of variables that were affected by partial harvest, whereas stand characteristic models consisted of variables that were less or not influenced by partial harvest compared to variables in silvicultural models. Again, some variables were in both categories, because silvicultural treatments could modify their effects on stem diameter variation. Dividing variables in these two groups differentiated the effect of harvesting over the baseline effect of the unharvested plot on daily stem diameter variation.

Table 4. List of candidate models explaining daily stem diameter variation (*SDV*) of black spruce during the 2017 growing season. Variable selection was based upon effects of silvicultural treatments and stand characteristics: silvicultural treatments (TREAT) with three different levels (control, partial harvest, girdling); precipitation (PREC); standardized water table depths (WTD); temperature (TEMP); canopy openness (CANOP); organic matter depths (OMD); and feather moss and sphagnum (FEA, SPH). The third column includes the expected effect, the hypotheses tested and the associated references.

Model Type	Candidate Models	Expected Effect and Hypotheses Tested
Silvicultural models	SDV ~ WTD + PREC + TREAT	Negative effect of water table depth and precipitation. Differences among treatments [20,21,29], H4
	SDV ~ WTD + TREAT + PREC + TREAT: PREC	Negative effect of water table depth. Different effects of precipitation among treatments [20,21,29], H4
	SDV ~ PREC + TREAT + WTD +TREAT: WTD	Negative effect of precipitation. Different effect of water table depth according to the treatments [20,21,29], H4
	SDV ~ WTD + PREC + TREAT+ TREAT: PREC + TREAT: WTD	Most complex silvicultural model.
Stand characteristics models	SDV ~ OMD + PREC + CANOP + TEMP + WTD	Negative effect of precipitation, organic matter depth and high water table. Positive effect of high temperature and low canopy openness [14,19–21,29], H4
	SDV ~ WTD + FEA + SPH + OMD	Negative effect of water table depth, hummock sphagnum and organic matter depth. Positive effect of large feather moss coverage [19,20,43], H4
	SDV ~ TEMP + CANOP + PREC + CANOP: PREC	Positive effect of high temperature, different effect of precipitation following canopy openness [20,29]
	SDV ~ TEMP + CANOP + PREC	Positive effect of high temperature and low canopy openness. Negative effect of precipitation [20,29].
	SDV ~ OMD + TEMP + CANOP + PREC+WTD + FEA + SPH + CANOP: PREC	Most complex stand characteristics model.
SDV ~ 1		Null model.

Model selection and multimodel inference was performed for both response variables with *AICcmodavg* package in R [53]. We estimated model-averaged effects of each parameter appearing in the models showing best fit in terms of ΔAIC_c (<4).

3. Results

3.1. Daily Variation in Water Table Depth before Silvicultural Treatments

The Figure 2 present the time trends of water table depth and the daily variation in water table depth (ΔWT) regrouped by treatment over the course of the study, before silvicultural treatment.

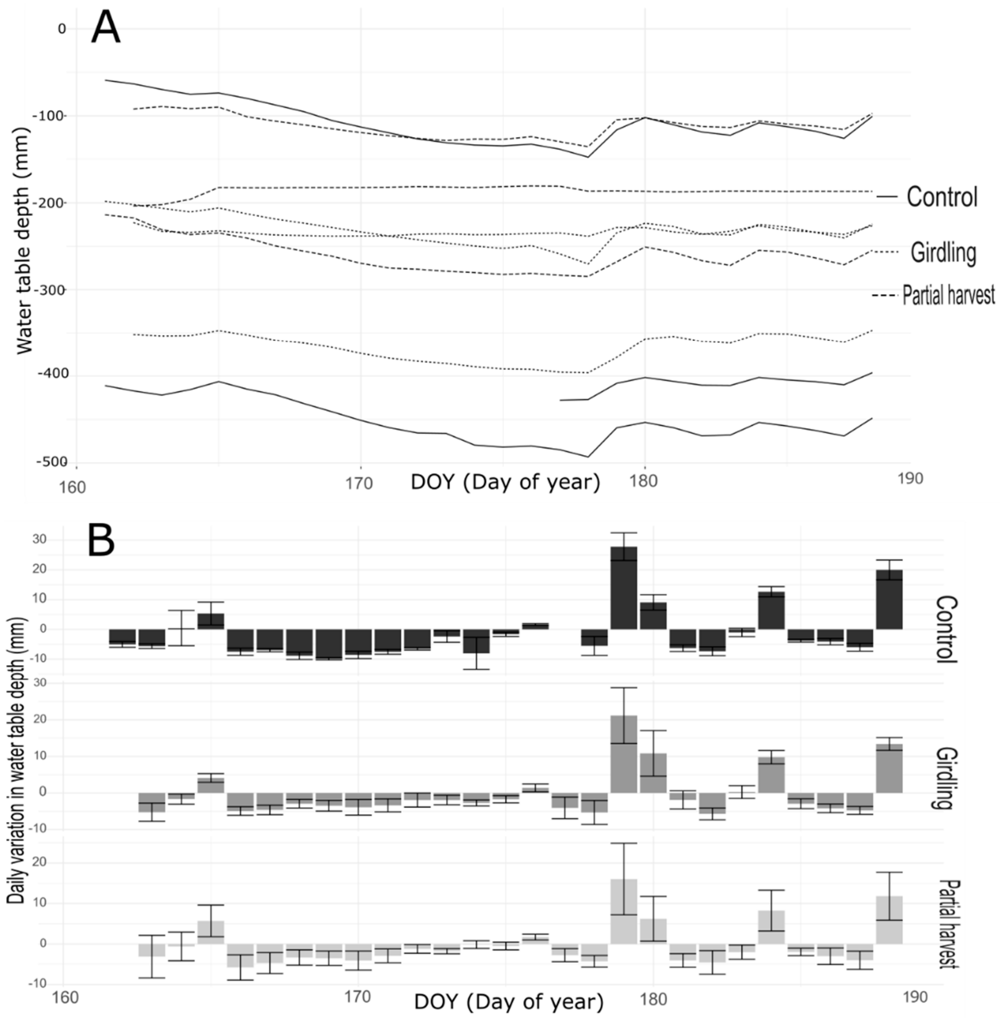

Figure 2. Water table movement throughout the growing seasons of 2016, before the sylvicultural treatments. (**A**) water table depth of each plot according to treatment. (**B**) Mean daily variation in water table depth (ΔWT) with standard error (mean ± SE) Each daily variation in water depth is a mean based on water table depth of three different plots for each treatment. The missing data for the water table depth are due to technical problems.

Stand characteristic models ranked higher than silvicultural treatment models in explaining daily variation in water table depth (ΔWT); four of the first five models were in this category (Table 5). This dominance of stand characteristic models in the models ranking was expected before silvicultural treatments. The highest ranked model included the additive effect of temperature and the interaction between precipitation and canopy openness (Table 5). Coefficients of determination (marginal R^2) of the different models were similar, ranging between 0.29 and 0.31 (Table 5). The residual variance showed in each table correspond to the variance not explained by the model.

Table 5. Most parsimonious models of silvicultural treatment and stand characteristic explaining daily variation in water table depth (Δ*WT*) before treatments, including the number of parameters (K), difference in AIC_c compared to the highest-ranked model (ΔAIC_c), AIC_c model weight (AIC_cWt), and predictive power (marginal R^2). Parameters appearing in the second portion of the table show the variables for which 95% confidence intervals exclude 0 and that influenced the response variable. The count of parameters includes the variance associated with the random-block effect, the treatment within-random-block effect and the residual variance. Note that girdling was the reference level of the treatment variable.

Candidate Models	*K*	Δ*AICc*	AIC_cWt	R^2	*Residual Variance*
ΔWT ~ TEMP + PRECL + CANOP + PRECL: CANOP	9	0.00	0.21	0.30	0.173
ΔWT ~ WTD + TREAT + PRECL + TREAT: PRECL	11	0.10	0.20	0.31	0.171
Parameters		**Lower 95% CL**	**Model-averaged estimate (β)**	**Upper 95% CL**	
Temperature (TEMP)		0.001	0.02	0.03	
Precipitation lagged by one day (PRECL)		0.18	0.23	0.27	
Treatment (Control): Precipitation (PRECL)		0.02	0.13	0.25	

Three variables exhibited significant effects on the response variable: precipitation lagged by one day; temperature; and the treatment by precipitation interaction (Table 5, Figures 3 and 4). Daily variation in water table depth increased with the amount of precipitation, although precipitation effects were slightly greater in control plots compared to girdling (Figure 3). Water table depth differences increased with temperature, but the effect was weak, as seen from increasing confidence interval widths with larger rain events (Figure 4). This interaction between treatment and precipitation before treatment can be attributed to the natural condition of the stand and precipitation interacting differently on Δ*WT* prior to treatment.

3.2. Daily Variation in Water Table Depth after Silvicultural Treatments

The Figure 5 present the time trends of water table depth and the daily variation in water table depth (Δ*WT*) regrouped by treatment over the course of the study, after silvicultural treatment. Each plot has the same behavior to drought and rain events over the course of the season (Figure 5).

With few minor differences, stand characteristic models for the period after treatment application still showed better fit in terms of AIC_c weights than did the silvicultural treatment models (Table 6). The highest-ranked model consisted of the additive effect of precipitation lagged by one day and the temperature ×canopy openness interaction (Table 6). Predictive power (R^2) of the two top-ranked models after treatment application was 0.41 (Table 6). However, the parameters influencing the Δ*WT* were the precipitation, the temperature and the interaction between precipitation and treatment (Table 6). The interaction effect between precipitation and control and partial harvest, the same relation as before treatment (Figures 3 and 6). This result suggests no changes in Δ*WT* before and after silvicultural treatments (Figures 3 and 6).

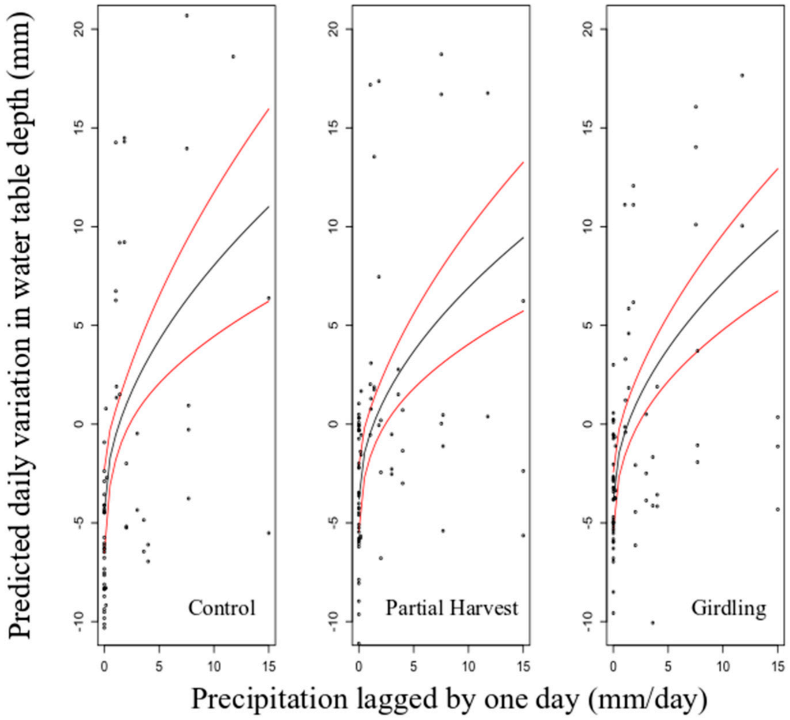

Figure 3. Predicted daily variation in water table depth before treatments based upon precipitation lagged by one day (mm/day) interacting with silvicultural treatment (Control, Partial harvest and Girdling). Model-averaged predictions using the entire set of candidate models are included with 95% CI. Open circles correspond to the original observations. Note that in this figure, daily variation in water table depth was back-transformed from square-root values. The figure shows the effect of variables having the greatest influence on the response variable.

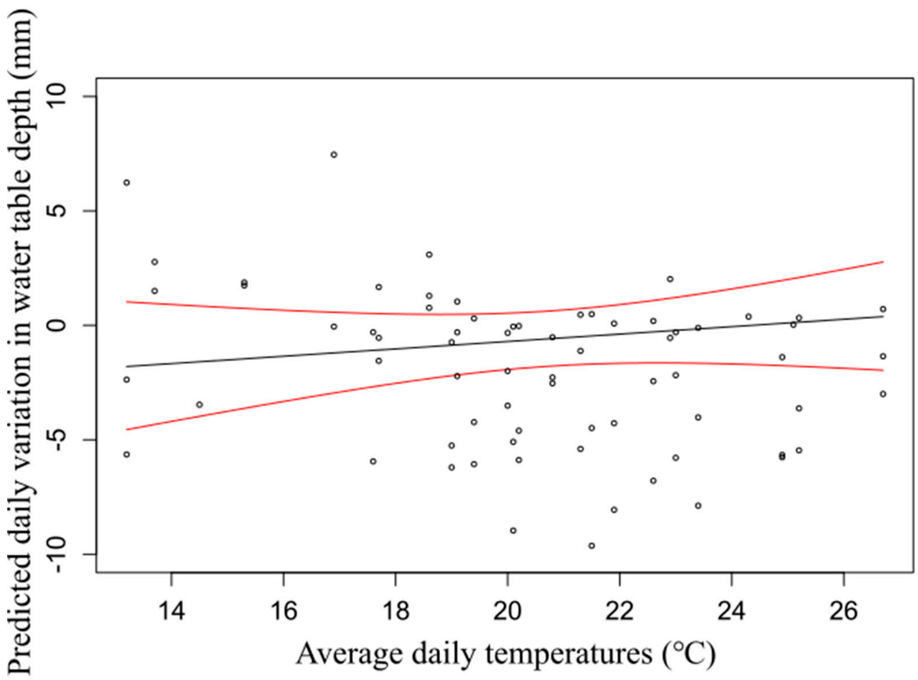

Figure 4. Predicted daily variation in water table depth before treatments based upon average daily temperatures (°C). Model-averaged predictions using the entire set of candidate models are included with 95% CI. Open circles correspond to the original observations. Note that in this figure, daily variation in water table depth was back-transformed from square-root values.

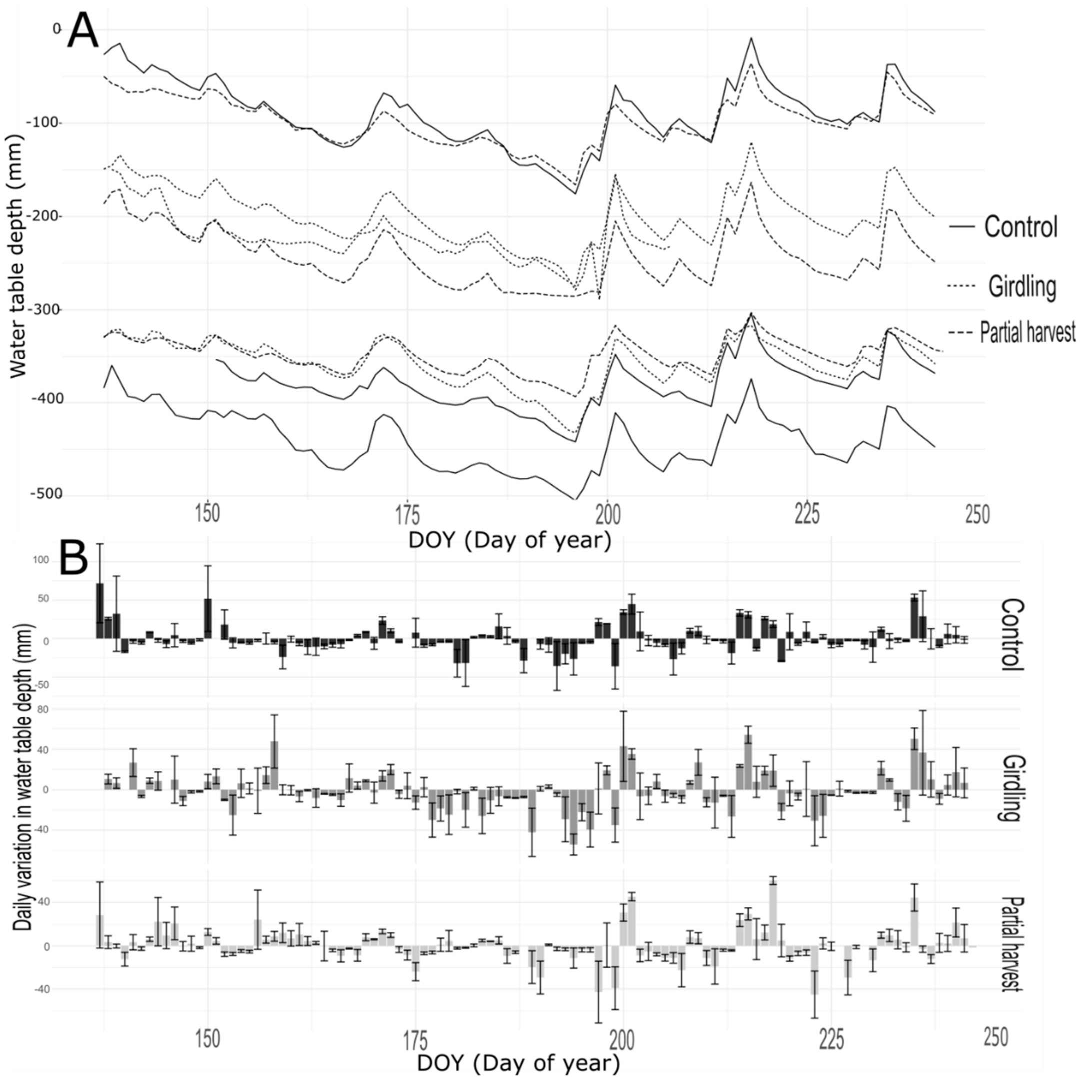

Figure 5. Water table movement throughout the growing seasons of 2017, after the sylvicultural treatments. (**A**) water table depth of each plot according to treatment. (**B**) Mean daily variation in water table depth with standard error (mean ± SE) throughout the growing seasons of 2017, after the sylvicultural treatments. Each daily variation in water depth is a mean based on water table depth of three different plots for each treatment. The missing data for the water table depth are due to technical problems.

Table 6. Most parsimonious models of silvicultural treatment and stand characteristic explaining daily variation in water table depth (Δ*WT*) after treatment, including the number of parameters (*K*), difference in AIC_c compared to highest-rankedmodel (ΔAIC_c), AIC_c model weight (AIC_cWt), and predictive power (marginal R^2). Parameters appearing in the second portion show the variables for which 95% confidence intervals exclude 0 and that influenced the response variable. The count of parameters includes the variance associated with the block random effect, the treatment within block random effect and the residual variance. Note that girdling was the reference level of the treatment variable.

Candidate Models	*K*	Δ*AICc*	AIC_cWt	R^2	*Residual Variance*
ΔWT ~ PRECL + CANOP + TEMP + CANOP: TEMP	9	0.00	0.25	0.41	0.416
ΔWT ~ WTD + PRECL + TREAT + WTD: PRECL + TREAT: PRECL	12	0.28	0.22	0.41	0.417
Parameters		**Lower 95% CL**	**Model-averaged estimate (β)**	**Upper 95% CL**	
Temperature (TEMP)		0.02	0.03	0.04	
Precipitation lagged by one day (PRECL)		0.35	0.37	0.40	
Treatment (Control): Precipitation (PRECL)		2.2×10^{-2}	8.4×10^{-2}	1.4×10^{-1}	

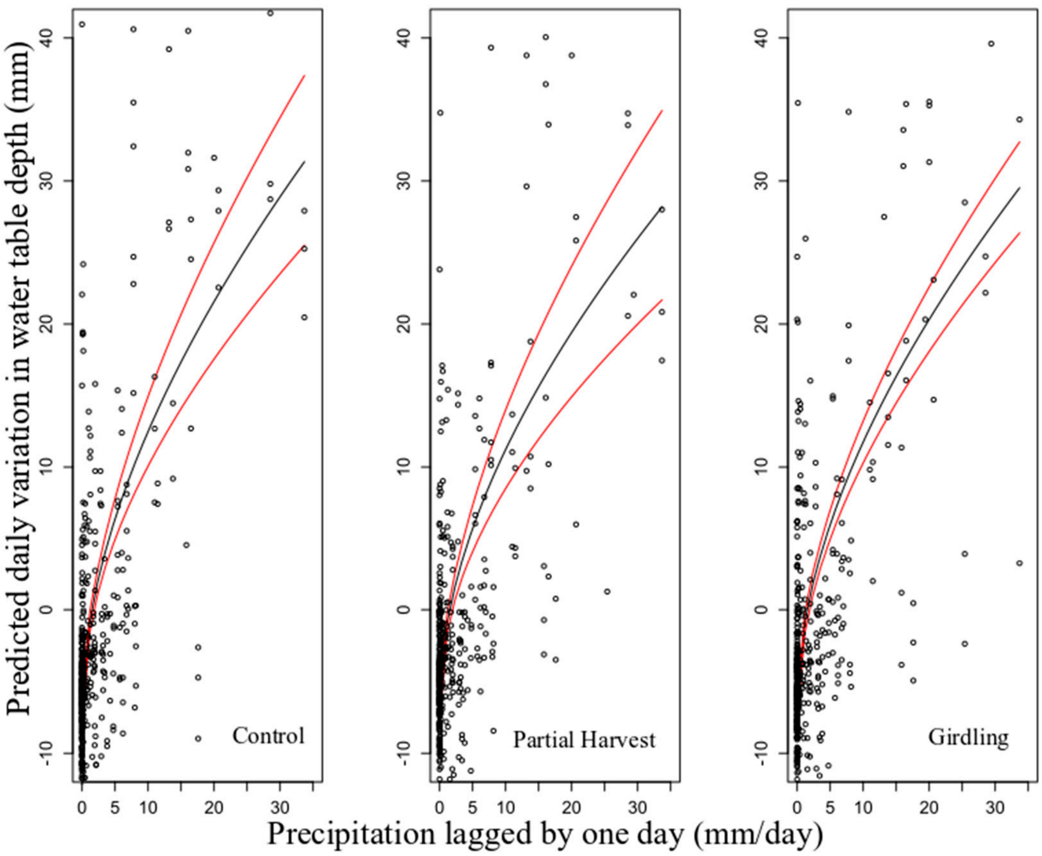

Figure 6. Predicted daily variation in water table depth following silvicultural treatments, based upon precipitation lagged by one day (mm/day) and silvicultural treatment (Control, Partial harvest and Girdling). Model-averaged predictions using the entire set of candidate models are included with 95% CI. Open circles correspond to the original observations. Note that in this figure, daily variation in water table depth was back-transformed from square-root values. The figure shows the effect of variables having the greatest influence on the response variable.

Daily variation in water table depth (Δ*WT*) increased with temperature (Figure 7). Average daily temperatures had the same positive effect both before and after treatments

(Figures 4 and 7). However, a comparison of the effect of temperatures between periods (before and after treatment) reveals a stronger positive post-treatment effect (Figure 7).

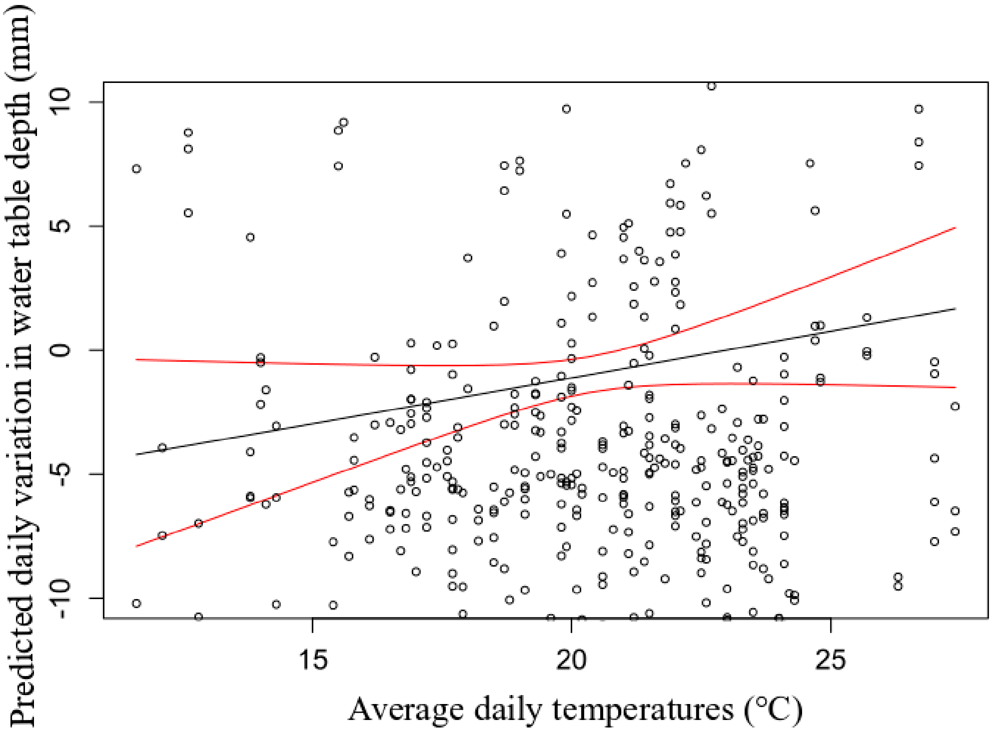

Figure 7. Predicted daily variation in water table depth after silvicultural treatment, based upon average daily temperatures. Model-averaged predictions using the entire set of candidate models are included in 95% CI. Open circles correspond to the original observations. Note that in this figure, daily variation in water table depth was back-transformed from square-root values. The figure shows the effect of variables having the greatest influence on the response variable.

One year after treatment, there was no difference between these treatments when we compared their Δ*WT* after and before the harvest (Figures 3 and 6).

3.3. Variation in Black Spruce Stem Diameter Following Silvicultural Treatments

A model including temperature and the interaction between precipitation and canopy openness exhibited the best fit among the candidates (*AICcWt* = 0.95, Table 7). This model had a lower predictive power than models for Δ*WT* (marginal R^2 = 0.23). The top model included stand characteristics, whereas silvicultural models were very weakly supported by our data (Table 7).

Variation of stem diameter increased weakly with temperature (Table 7, Figure 8). A closed canopy resulted in greater stem diameter variation during larger rain events (Figure 8). Large rain events also increased diameter variation in more open stands, but to a lesser extent when compared to closed canopy stands (Figure 8). The variation of stem diameter was not influenced by Δ*WT* which was not expected for our fourth hypothesis. Even if not change was observed on Δ*WT* throughout treatment, we were expecting negative impact of high Δ*WT* on stem diameter variation.

Table 7. Most parsimonious model explaining daily variation of stem diameter (*SDV*) with the number of parameters (*K*), difference in AIC_c compared to highest-ranked model (ΔAIC_c), AIC_c model weight (AIC_cWt) and the predictive power (marginal R^2). Parameters appearing in the second portion of the table show variables for which 95% confidence intervals exclude 0 and that influenced the response variable. Note that the count of parameters includes the variance associated with the random-block effect, the treatment within-random-block effect and the residual variance.

Candidate Models	*K*	$\Delta AICc$	AIC_cWt	R^2	*Residual Variance*
SDV ~ TEMP + CANOP + PREC + CANOP: PREC	8	0.00	0.95	0.23	0.416
Parameters		**Lower 95% CL**	**Model-averaged estimate (β)**	**Upper 95% CL**	
Temperature (TEMP)		8.37×10^{-3}	1.09×10^{-2}	1.34×10^{-2}	
Canopy openness (CANOP): Precipitation (PREC)		1.81×10^{-3}	2.51×10^{-3}	3.20×10^{-3}	

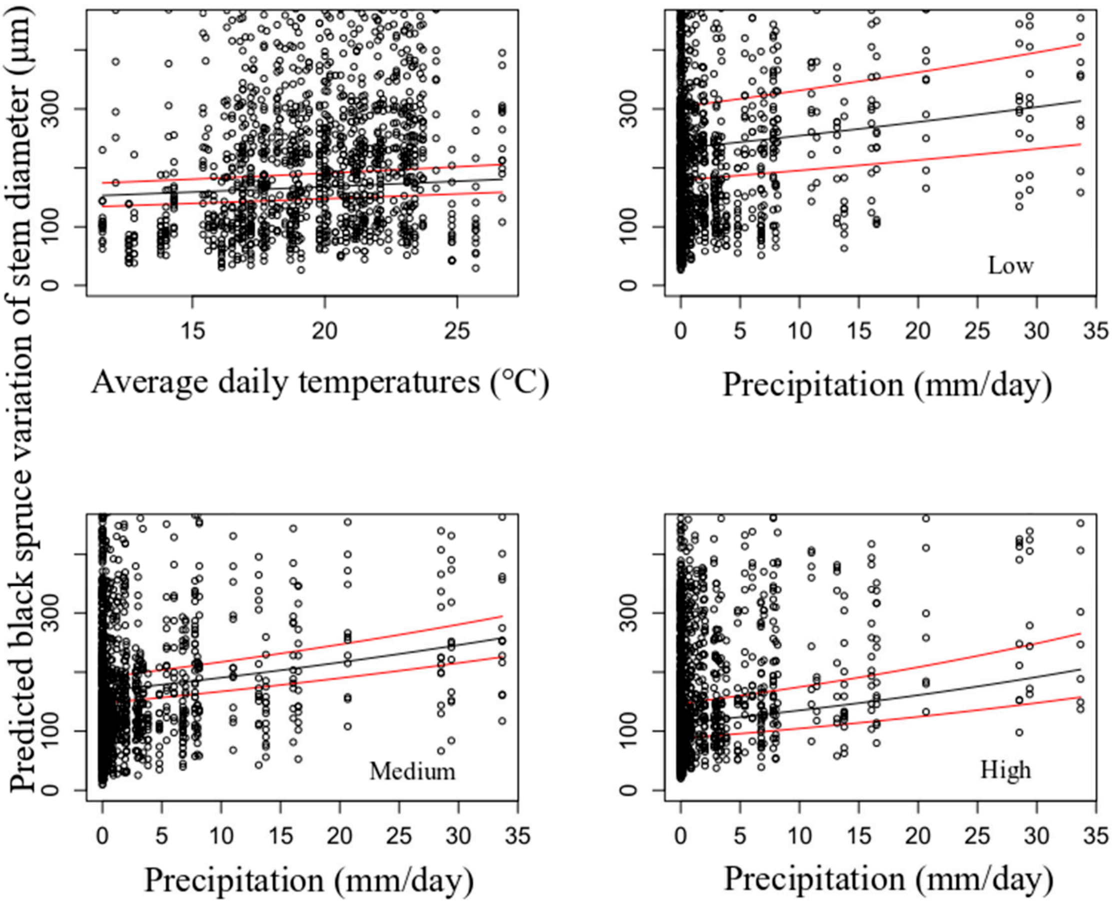

Figure 8. Predicted daily stem diameter variation of 45 black spruce that were sampled as a function of temperature and canopy openness (low = 21%; medium = 31%; high = 43%), interacting with precipitation during the 2017 growing season. Model-averaged predictions using the entire set of candidate models are included with 95% CI. Open circles correspond to the original observations. Note that in this figure, diameters were back-transformed from the logarithmic scale. The figure shows the effect of variables having the greatest influence on the response variable.

4. Discussion

Our short-term study, conducted during the growing seasons of 2016 and 2017, measured responses of daily fluctuations in water table depth (ΔWT) prior to silvicultural treatments and following silvicultural treatments. The daily fluctuations in water table depth (ΔWT) increased with temperature and precipitation, although the relationship with the latter variable depended upon treatment (precipitation $\times$ treatment interaction) (Figures 2 and 3). This interaction represents the difference of throughfall between silvicultural treatments in our study. However, we are not linking this throughfall difference to the effect of partial harvest on the interception. Indeed, the same variables had effects both before and after treatment, but our study did not detect any changes in ΔWT related to partial harvesting or girdling treatments one year after treatment. This lack of effect of partial harvesting might be due to a true absence of short-term effects of partial harvesting or due to a lower power of detection of such an effect due to low sample size in our study. Furthermore, ΔWT models showed that stand characteristics had greater effects than did silvicultural treatments on ΔWT, but mainly through the effect of temperature.

Stem diameter variation in the black spruce retained on site was driven by temperature and precipitation interacting with canopy openness, which is consistent with the observations of Deslauriers et al. [29]. Variation of stem diameter was independent of water table depth, contrary to our hypothesis. This result was likely due to minor changes in soil hydrology and temperature between partial harvest and control plots, as Brais et al. [54] have previously described for the same time period following harvest. Because we studied the short-term effect of partial harvest on stem diameter and water table depth, the trends observed in this study could change over time and requires further investigation.

4.1. Effect of Partial Harvest on Variation in Water Table Depth and Black Spruce Stem Diameter

Overall, our results suggest that partial harvest of 40% of the basal area does not influence daily variation in water table depth one year following treatment (Figures 3 and 6). This response is supported by the weak predictive power offered by silvicultural treatments on variation in water table depth between periods (Tables 5 and 6). Therefore, the interaction between precipitation and silvicultural treatment was the best predictor of the response variable both before and after treatment. If the silvicultural treatments have had an impact on ΔWT on year after treatment, we would have observed different effects between periods. Consequently, neither partial harvest nor girdling influenced daily variation in water table depth beyond that of the control (Figures 3 and 6). Finally, the Figures 2 and 5 confirmed to us that the treatments were distributed at different water table depth. It would have been problematic for the interpretation of the result if the water table depth of each treatment were regrouped at the same depth.

Our first hypothesis comparing partial harvest with girdling advanced that differences between the treatments would isolate the effect of interception on water table depth. This suggests that the effect of the interception alone does not influence ΔWT for this period of time and basal area removal. Furthermore, our results showed no difference between partial harvest and control throughout the study, thus rejecting our second hypothesis and confirming our third hypothesis. One year after treatment, we did not find an effect of treatment alone, but we did find an interaction between treatment and precipitation relative to the control in our study. Yet, since control interacting with precipitation had greater daily variation in water table depth than the two other treatments, this suggests that interception and transpiration had no appreciable effect on daily variation in water table depth. However, the effect of interception could be significant over a longer period of time as observed by Dubé et al. [23]. Furthermore, the highest-ranked models of daily variation of water table depth were based upon stand characteristics. This result may be attributed to the low degree of canopy openness that was created by the partial harvest, which presumably was not sufficient to influence the water table, and to small changes in interception and transpiration rates one year after treatment (Table 1). This absence of effect could be linked to the shape or architecture of black spruce trees, given that conifers do not intercept a large portion of precipitation that falls, particularly during large rainfall events [27]. Furthermore, black spruce transpiration rates are low [29]; as we had hypothesized, the transpiration effect seems to be negligible given that fluctuations of the water table in girdled plots did not differ from those of the partial harvest and control treatments (Figures 3 and 6). The lack of an effect persisted, even when testing the treatment effect in interaction with basal area. Our study investigated short-term effects of light partial harvest and girdling, but the treatment might have an effect over a longer period. For instance, the cumulative effect of transpiration and interception reduction over time could raise the perched water table. Harvesting routinely raises the water table between 2.6 and 22 cm in similar environments [23–26]. Roy et al. [25] showed short-term (3 year) elevation of the water table, ranging between 5 and 13 cm. These rises occurred after clearcuts in peatlands, which means that we can expect smaller increases in our case, based upon the partial harvest treatment that was applied [55]. Furthermore, 10 years after clearcutting, the water table can still be elevated 5 to 7 cm above than its initial state [52]. Finally, Hökkä and Penttilä [56], reported no rise in water table levels for Scots pine (*Pinus sylvestris* L.) stands after thinning. This type of harvesting was closer to own our partial harvest treatment than was clearcutting with careful logging.

Deslauriers et al. [29] stated that turgidity responds more rapidly to environmental changes than does growth. This is why we used variation in stem diameter as a proxy in our study. Slowly-growing trees, such as black spruce, exhibit greater stem diameter variations due to water uptake, rather than due to xylem deposition [29]. Having measured only one year of stem diameter variation we focused on the effect of ΔWT on daily stem diameter variation. We are not able to detect stem diameter variation changes between period and deeply investigate the effect of treatments on this variable. However, since we applied partial harvest and girdling on black spruce stands, we also tested the effect of these treatment on stem diameter variation. Variation of stem diameter did not show any effect that was linked to silvicultural treatments. We expected a negative effect of high water table on black spruce growth and turgidity, but no such effect occurred. In fact, we did not find changes in water table depth following treatments, yet we would expect that a rise in the water table would reduce black spruce turgidity and growth [57,58]. The effect of new foliage growth under an increasingly open canopy that was induced by partial harvesting would accumulate over a couple years to positively influence black spruce growth. The lifespan of black spruce needles is estimated at about 7–10 years, with a maximum of 15 years [59]. Furthermore, Thorpe et al. [60] showed a two-year delay in the response of black spruce growth to partial harvesting under similar conditions in Ontario. Therefore, to make more definitive conclusions regarding black spruce growth and turgidity, we must wait at least two years following treatments to capture potential beneficial effects [60]. The partial harvest treatment did not influence variation in stem diameter on our study site, which suggests that the changes were not sufficiently drastic to elicit a response in growth patterns.

These results do not mean that we can ignore the potential negative effects of silvicultural treatments on water table depth and stem diameter fluctuations. The potential negative effects can be expect over a longer horizon such as: water table can rise and enhance sphagna growth decreasing the stand productivity [17,22]. Indeed, we noted a marginal effect of canopy openness on variation in stem diameter. As a result, removal of a greater portion of the basal area could decrease the fluctuations in stem diameter and could also elevate the water table.

4.2. Effects of Canopy Openness on Variation in Water Table Depth and Variation in Black Spruce Stem Diameter

Our second hypothesis stated that the most important factor explaining daily variation in water table depth would be a reduction of interception one year after partial harvesting. The effect of interception was also tested through the effect of canopy openness. Canopy openness prior to treatment application emerges as one of the most important stand features in this environment, given that this variable appeared in all top-ranked models. Reduction in interception and transpiration that was induced by partial harvest did not influence daily variation in water table depth, except through a marginal interaction between precipitation and treatment. Since the silvicultural treatment was coded as a dummy variable, we could test this effect prior to treatment applications; the effect was the same following the partial harvest. Variation in black spruce stem diameter increased with precipitation interacting with low canopy openness. This trend revealed that trees growing within closed canopy had greater variation in stem diameter than did trees in more open stands following large rainfall events. Less open stands would drawdown the water table, thereby promoting variation in stem diameter and growth [58]. Canopy openness is also linked with the interception rate (mm per day) of the stand [25]. This result suggests that a partial harvest of 40% in paludified black spruce stand is not changing interception and that the natural spatial variability of canopy openness exerts a greater effect on the water table. We know that a predominantly open canopy increases incident light, which in turn leads to increased temperatures and decreased soil moisture after harvest [61,62]. Furthermore, harvests with high canopy retention should limit the expansion of light-demanding *Sphagnum* species, given that these are rarely found in microhabitats with less than 40% open canopy [63]. In our case, we wanted to limit as much as possible the expansion of light-demanding *Sphagnum* species, which are linked with higher paludification rates. In terms of the degree of basal area retention that is required, between 40 and 60% cover is needed to maintain at least pre-harvest biodiversity [20]. *Sphagnum* communities are similar between partial harvest sites compared to those in old-growth forests [43].

Our short-term study was conducted over two growing seasons. Ideally, the pretreatment period would have been longer and data collection would have extended a year after treatment. The lack of data on rain events on each plot was also a limitation of our study. Another way to test the treatment effect on ΔWT would be to measure throughfall on each plot and to see its interaction with silvicultural treatments. Yet, a larger number of plots would have allowed us to better explain the response variables and to improve statistical power. The next approach would be to focus on fewer variables of interest (canopy openness, basal area, rain and temperature), while sampling a larger number of plots to clearly detect the effect of partial harvest on water table and residual trees growth and turgidity. Only having one growing season of variation in stem diameter also limit the scope of our interpretation.

4.3. Management Implications

Our study showed that partial harvesting of 40% did not induce notable changes in either daily fluctuations of water table depth or on variation in black spruce stem diameter (Figures 3, 6 and 8). Even though silvicultural treatments did not exert a strong effect on either daily variation in water table depth or stem diameter fluctuations, we emphasize that temperature and canopy openness interacting with precipitation had good predictive power with respect to both variables of interest. Furthermore, we know that clearcuts on organic soils lead to water table rises ranging between 2.6 and 22 cm [23–26]. Consequently, we must be careful in our management practices and we should limit canopy openings that are created by silvicultural treatments. Pothier et al. [28] and Heikurainen and Paivanen [55] demonstrated that water table elevation following harvest is proportional to cutting severity, thereby confirming our results of partial harvest and canopy openness effects on fluctuations in water table depth.

However, we believe that using partial harvest in heavily paludified stands with low basal areas would not promote the growth of residual trees, but organic matter accumulation [17,43]. Partial harvesting should be applied to stands with high merchantable basal area with understory trees that are ready to occupy the newly created space. In this case, partial harvests of 40% could be a sustainable management practice in black spruce stands of the boreal forest. A recent long-term study demonstrated the positive effect of partial harvesting on peatland black spruce stand characteristics, such as diameter, height, basal area crown ratio, structural complexity, and compositional diversity [64]. These benefits over the long term (57-year post-treatment) and in a similar forest are encouraging. However, this silvicultural treatment is only viable if the mortality of residual trees is low [18,28,60,65]. We hope that the removal of larger stems would reduce stand susceptibility to windthrow given that larger stems are more susceptible to such disturbance [66]. Furthermore, low basal area removal reduces the risk of losing residual trees [67–69]. MacDonell and Groot [70], and Groot [71] demonstrated the biological and technical feasibility of uneven-aged silviculture in peatland black spruce stands. Even if the economic aspect of this management is less attractive, it decreases the risk of post-logging regeneration failure due to increased paludification [72].

Regarding biodiversity, partial harvests with levels of retention above 66% of canopy cover would contribute to maintaining some old-growth stand structure that are needed by bird communities [20,73]. Partial harvesting provides sufficient deadwood to maintain boreal small mammal communities [74]. Basal area retention between 40 and 60% is needed to maintain at least pre-harvest biodiversity for a large range of taxa [20]. This retention level is similar to harvest levels that we have suggested, which are inducing changes neither in water table depths nor on black spruce potential growth. Fenton and Bergeron [43] showed that partial harvest shifts *Sphagnum* species toward old-growth forest communities rather than peatland sphagnum species since such communities are a useful indicator of old-growth forest characteristics. Forest management certification should be considered and seen as an incentive for including more partial harvest operations [75].

5. Conclusions

Our study showed the potential of a light partial harvest for avoiding both water table rise and its negative effects on stand productivity one year after harvest. Our results support the hypothesis that light silvicultural treatment in black spruce forests mitigate water table rise compared to clearcutting harvest [23,28]. A follow-up study is mandatory to investigate further on the effect of partial harvest on water table and variation in stem diameter in the longer term. However, we highlight the importance of canopy openness and precipitation regardless of the effect of silvicultural treatments on variation in stem diameter, to maintain ecosystem dynamics and stand productivity shortly following harvesting. Temperature influenced both variation in stem diameter and variation in water table elevation, reiterating the importance of climate change on boreal forest dynamics. A partial harvest of 40% on the merchantable basal area seems to be a more appropriate management practice for supplying wood and preserving ecosystem integrity in this challenging environment.

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