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# Development and Evaluation of Black Spruce (*Picea mariana* (Miller) B.S.P.) Diameter Increment Models across Silvicultural Treatments in Northern Minnesota, USA

Brian D. Anderson <sup>1,\*</sup>, Matthew B. Russell <sup>1</sup> , Marcella A. Windmuller-Campione <sup>1</sup>,  
Brian J. Palik <sup>2</sup> and Douglas N. Kastendick <sup>2</sup>

<sup>1</sup> Department of Forest Resources, University of Minnesota, St. Paul, MN 55108, USA; russellm@umn.edu (M.B.R.); mwind@umn.edu (M.A.W.-C.)

<sup>2</sup> USDA Forest Service Northern Research Station, Grand Rapids, MN 55744, USA; bpalik@fs.fed.us (B.J.P.); dkastendick@fs.fed.us (D.N.K.)

\* Correspondence: and03662@umn.edu; Tel.: +1-612-624-3400

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**Abstract:** The black spruce cover type occupies roughly 10% of Minnesota’s 7 million hectares of forestland, and is an important species, both ecologically and economically. A clearcut regeneration harvest is the main silvicultural system in black spruce in this region. The effects of managing black spruce with alternative silvicultural methods in the Lake States remains largely understudied. Here, we examine a silviculture study in lowland black spruce to assess the performance of two diameter growth models fit to this data compared to a widely-used model. Six silvicultural treatments (clearcut strips, clearcut patches, thinning, group selection, single-tree selection, and shelterwood) and a control were treated and measured around 1950, with a follow-up measurement occurring 10 years later. Fixed- and mixed-effects growth-models were adapted from the previous work, and fit to 10,231 observations and compared to a recently released diameter growth model. The mixed-effects model using treatment, compartment, and plot as nested random effects outperformed the fixed-effects model, and outperformed a model proposed for use in the Lake States variant of the Forest Vegetation Simulator that was fit to this data. This modeling approach of localized growth models across a wide-range of diameters (9.1–32.1 cm) more accurately predicted the diameter growth in lowland black spruce than the conventional approach of using separate models for large (>12.7 cm) and small ( $\leq 12.7$  cm) diameter trees.

**Keywords:** peatland black spruce; lowland black spruce; silviculture; diameter growth modeling

## 1. Introduction

Black spruce (*Picea mariana* (Miller) B.S.P.) is distributed broadly across North American boreal forests, and is an important species, both economically and ecologically [1]. Black spruce is the most important pulpwood species in Canada, and it is a major commercial species in the Lake States region (Michigan, Minnesota, and Wisconsin) of the United States [1]. In Minnesota, black spruce comprises 648,000 hectares of the 7.04 million forested hectares [2] and is the second-most harvested pulpwood species by volume [3].

Across the US Lakes States, black spruce is near its southern and western range limit. Black spruce can occur under a variety of environmental conditions in both pure and mixed composition stands. Black spruce is the dominant overstory species in the black spruce/feather moss-lichen forest type, and is a co-dominant species in five other forest types [4]. In Minnesota, black spruce can occur on

both upland and lowland soils. However, in general, it is only a dominant species in lowland sites with low nutrient quality and poor drainage [4]. On high quality sites, lowland black spruce in Minnesota can reach a diameter at breast height (1.3 m above the ground; DBH) of 35 cm, and a total height of 24 m. However, mature stands typically contain trees with diameters of 13 to 23 cm, and heights of 15 to 20 m [5]. Stand yields vary greatly, depending on site index, basal area, and age. Yields for a 120-year old stand (all trees over 9.1 cm) with a basal area of 27.5 m<sup>2</sup> ha<sup>-1</sup> ranged from 173 m<sup>3</sup> ha<sup>-1</sup> in a stand with site index of 10.7 m (base age 50 years), to 141 m<sup>3</sup> ha<sup>-1</sup> in the same stand at a site index of 7.6 m [6].

In Canada, there has been increased interest in understanding the growth dynamics of black spruce in both upland and lowland forests, in response to varying silvicultural systems. Black spruce diameter growth is influenced by tree and stand-level variables such as spatial position in a stand, distance relative to skidding trails, competition, growth prior to cutting, diameter, and tree age [7–9]. In response to silvicultural systems, Groot and Hokka [10] demonstrated that in uneven-aged black spruce stands, the average diameter growth of advance regeneration responds positively over a 10-year period following a regeneration harvest, peaking at 10 years and slowly declining to near pre-harvest levels. Black spruce individual diameter growth has also been shown to respond favorably to a variety of silvicultural treatments, including thinning, shelterwoods, and partial selection cuts [7,8,11].

An important damaging agent in black spruce forests in the Lake States is eastern spruce dwarf mistletoe (*Arceuthobium pusillum* Peck), which is present in 12% to 55% of black spruce stands in Minnesota [12]. Dwarf mistletoe in black spruce stands affects both tree growth rates, and its presence thereof influences the selection of silvicultural systems used. Mistletoe greatly reduces growth, and eventually leads to the mortality of infected trees [1,12–14], resulting in volume losses of 14% to 30% over the course of a rotation [15,16]. Recommended management options for the control and eradication of the disease typically involves clearcutting with a buffer strip around known infections, and to avoid selection methods or other silvicultural systems with reserves [1,12,17–19].

While there has been continued research on black spruce stand development and growth in Canada, these recent studies may not be directly comparable to black spruce forests of the Lakes States region, due to different precipitation and temperature extremes and norms. There are few studies in the region in black spruce silviculture and growth and yield over the last 40 years. Previously, in the mid-20th century, there was considerable work exploring the impacts of alternative silvicultural systems on growth and yield [6,14,20,21]. Similarly, yield tables published by the US Forest Service in 1971 are commonly used today [6], but they have not been evaluated across a range of silvicultural systems.

Diameter growth is one common metric that is used to quantify the growth of managed forest stands [22,23]. Understanding individual tree diameter growth is important for land managers to assess how changing environmental conditions influence future productivity. Individual tree diameter increment models are used in many forest modeling systems, notably, the US Forest Service Forest Vegetation Simulator (FVS) program [24]. Work by Deo and Froese [25] to improve model fitting for large-diameter trees is currently being transitioned into use in FVS [24]. Despite this work, little is known about the long-term effects of silvicultural treatments on black spruce diameter growth.

The goal of this research is to develop and evaluate black spruce diameter increment models across a range of silvicultural systems in northern Minnesota, USA. The specific objective is develop and assess the performance of non-linear fixed- and mixed-effects models to predict 10-year diameter growth in lowland black spruce under a variety of silvicultural treatments and across a range of tree- and stand-level conditions.

## 2. Materials and Methods

### 2.1. Study Area

The Compartment Study is a long-term experiment located on the Big Falls Experimental Forest (BFEF) near Big Falls, MN, USA (48°21' N, 93°46' W, 371 m above sea level.). Minnesota is one of three states in the Lake States region, an area near the western Great Lakes and south of the border with Canada. The study occupies the lowland, or peatland, black spruce cover type, black spruce group (12) [4], and Native Plant Community type APn81 [26]. The climate is continental with short, warm summers and long, cold winters. Maximum summer temperatures can exceed 32 °C, with high humidity (80 percent), and minimum winter temperatures can reach −35 °C. Precipitation ranges from 500–640 mm, with average snowfall around 150 cm [27].

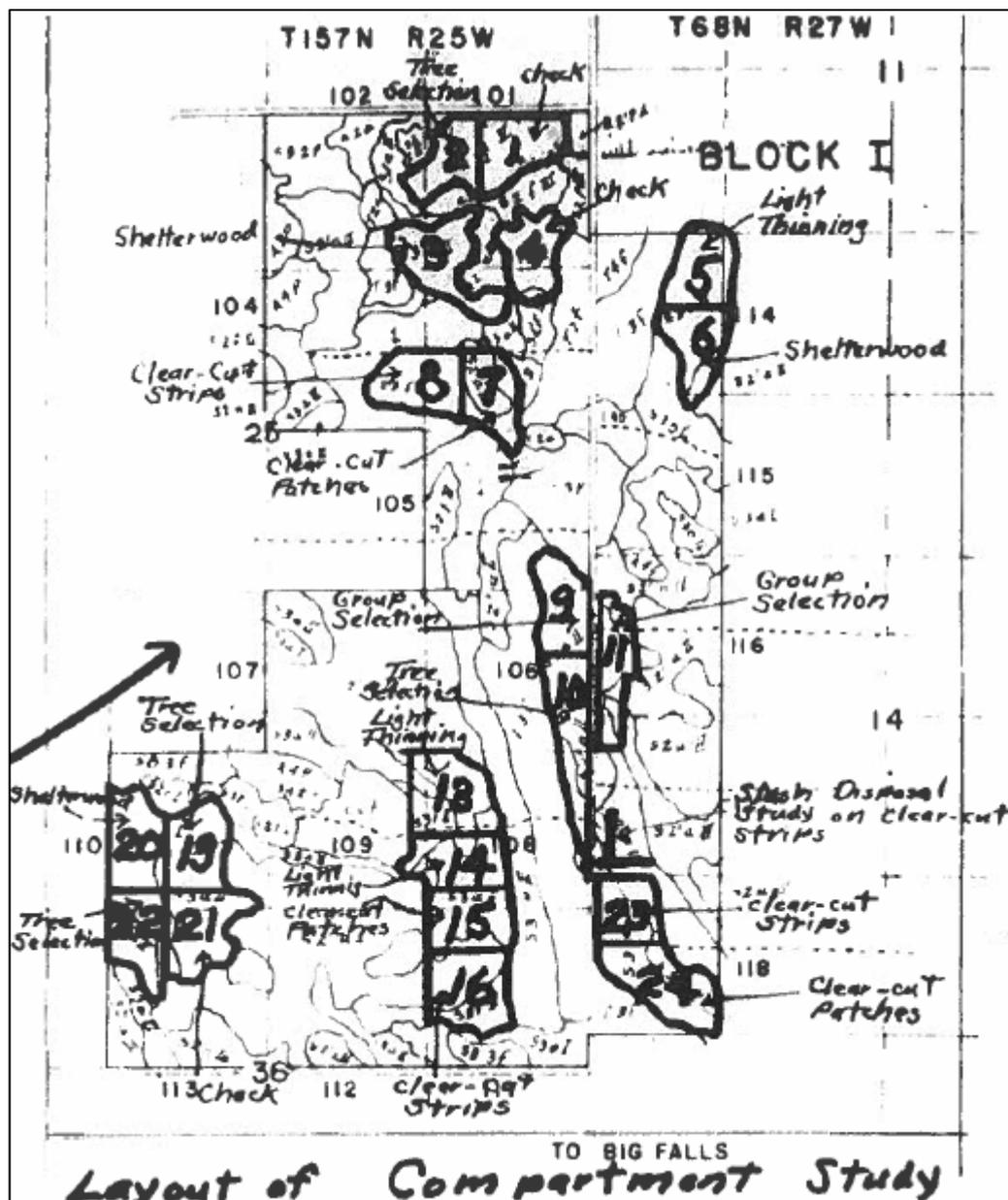
The BFEF was established in 1948 by an agreement between the Minnesota Department of Conservation (now the Minnesota Department of Natural Resources) and the United States Forest Service (USFS) Lake States Forest Experiment Station (now the USFS Northern Research Station). The agreement reserved 828 hectares of state-owned land for the purpose of silviculture, harvesting, and utilization, and economic studies in lowland conifers. The cover type at the time was being exploited and severely overcut [28]. The original goals of the Compartment Study were to examine the extension of the life and improvement in the productivity of these forests, and also included an investigation of regeneration after harvest, gathering information on site conditions and site determination, and studying the economic viability of various management practices in lowland black spruce [29,30].

### 2.2. Field Methods

Six silvicultural treatments and a control were implemented in 1948: Three even-aged treatments (clearcut strips, clearcut patches, shelterwood), two uneven-aged treatments (group selection, single-tree selection), and one intermediate treatment (light thinning). Treatments were carried out in a single winter between 1949 and 1951. The clearcut strips treatment consisted of 20- to 40 m wide strips oriented north–south to favor seed dispersal from westerly prevailing winds. Clearcut patches were 0.1 to 0.2 ha patches of any shape (Figure 1). Three or four entries over 17 years were utilized to cut the entire stand into both clearcut treatments. The shelterwood treatment was implemented with a shelterwood cut to an average basal area of 11.5 m<sup>2</sup> ha<sup>−1</sup>, leaving healthy and vigorous trees. The overstory removal cut was implemented 10 years after the shelterwood cut, with care taken to avoid damage to the understory. The single-tree and group selection cuts targeted individual trees or groups of four to eight trees, with openings not larger than nine to 12 m in diameter, with the goal of develop all-age conditions through variable cutting cycles. The thinning treatment was a free thinning to capture mortality through a variable cutting cycle of every eight to 10 years. The ideal scenario was that the light thinning treatment would be followed by a regeneration harvest; however, ultimately only the initial treatment was implemented.

Each treatment was replicated three times, totaling 21 compartments. Depending on the treatment, compartments contained eight to 16 permanent 0.4 ha plots, and ranged in size from 2.3 to 3.8 ha. Compartments were all located within two kilometers of each other (Figure 2). At the time of establishment, the 21 compartments ranged from 66 to 176 years old, stand structure was even- or uneven-aged, and site index (total height of dominant and co-dominant trees at 100 years) ranged from 9.1 to 18.3 m.





**Figure 2.** Map depicting the locations of the compartments and treatments in the Compartment Study on the Big Falls Experimental Forest in northern Minnesota, USA. Note that 12, 17, and 18 were unused in numbering the 21 compartments. Map courtesy of US Forest Service.

The initial measurement was taken prior to the initial treatment in all compartments between 1948 and 1950. Two additional measurements were taken—one about five years after the initial treatment, and another about 10 years after the initial treatment (referred to as the “10-year re-measurement”), just prior to the second treatment. All compartments were treated both initially and at 10 years, except for the control (which was left untreated) and the light thinning, which only received the initial treatment.

In the clearcut treatments, only plots that were not cut in the original treatment were re-measured, due to the immature size class of treated plots at the time of re-measurement. These uncut portions were removed in later treatments after the 10-year re-measurement, when strips and patches were expanded. Residual plot centers were as close as 15 m from areas that were removed with the initial treatment, meaning that trees on the outer edge of plots may have been within several meters from cut portions of the stand (Figure 1). As such, they are considered to be different from the controls, which had no portions of any plot come within the same proximity to harvesting.

Plot-level variables recorded for each plot were site index and age for each plot. Age was determined by coring two or three black spruce nearest to the plot center at breast height. Individual tree variables included species, diameter to 0.1 cm (all trees over 9.1 cm in DBH), crown class, crown vigor, and form or health descriptions of each tree. Individual trees within each plot were stem-mapped and numbered, and variables were recorded for specific trees with each measurement. Repeated measurements on tagged trees allowed for the diameter and other variables to be monitored over time. A link to the data used can be found in the Supplementary Materials.

### 2.3. Analysis

Ten-year DBH growth was calculated as the difference between DBH at measurement one (around 1950) and DBH at measurement three (around 1960). Some compartments were re-measured nine or 11 years after the initial measurement. In such instances, 10-year DBH change was standardized by calculating the difference in DBH from measurement one to measurement three, dividing by the number of years between measurements, and multiplying by 10. Plot-level basal area was calculated by expanding to a per hectare basis.

#### 2.3.1. Ten-Year Diameter Growth Model

A series of diameter growth models was formulated to predict 10-year diameter increment from the initial to the 10-year measurement. A model from Hann et al. [22] was adapted, as it has proven to be successful in modeling the diameter growth in other species [31], including black spruce [23].

Crown position was originally recorded for each tree on a scale of seven classes: head dominants, strong dominants, conditional dominants and codominants, weak dominants and codominants, intermediates, suppressed trees, and open grown trees. To align with the more commonly used indicators, these were converted to four crown classes that are often used, by using descriptions of the original classes in the original working plan [30]: dominant, codominant, intermediate, and suppressed. The revised four-class crown position variable was then fit with a dummy variable where dominant and codominant trees were given a value of 1, and where intermediate and suppressed trees were 0.

The Hann et al. [22] model includes the crown ratio as a predictor variable; however, crown ratio was not measured in the Compartment Study. Instead, the revised four-class crown position variable mentioned above was fit with the dummy variable for dominant/codominant and intermediate/suppressed trees. Predicting the crown ratio was considered instead of using a crown position indicator variable, but this was ultimately rejected in favor of fitting a model using only variables that were measured in the study. Additionally, age was taken at the plot level in the Compartment Study, and this was assessed as a possible predictor variable. The possible full equation based on all assessed variables was:

$$\Delta DBH = \exp(\beta_0 + \beta_1 \log(DBH + 1) + \beta_2 DBH^2 + \beta_3 Age + \beta_4 \log(SI - 1.37) + \beta_5 \frac{BAL^2}{\log(DBH + 5)} + \beta_6 \sqrt{BA} + \beta_7 CP) + \varepsilon_a \quad (1)$$

where  $\Delta DBH$  is 10-year diameter increment in cm,  $DBH$  is the diameter of the tree at initial measurement (cm),  $SI$  is the site index in m at 100 years,  $BAL$  is an individual tree asymmetric-based variable equaling the basal area of trees larger than the subject tree in a plot,  $BA$  is the stand basal area of the initial stand after all initial treatments,  $CP$  is crown class dummy variable equal to 1 for dominant and codominant trees, and 0 for all other crown classes, and  $\varepsilon_a$  is the within-tree error.

#### 2.3.2. Model Fitting

All model fitting was completed using R [32] and the NLME package [33]. Model fitting began by using only fixed effects as a generalized nonlinear least squares (GNLS) model (Equation (1)). Variables were added one at a time from the form suggested by Weiskittel et al. [31], and they were kept in the model by assessing how the variable affected the Akaike information criterion (AIC) value

for the model, and whether the coefficient for the variable was significant ( $p < 0.05$ ). AIC is defined as  $AIC = -2 \ln(L) + 2k$  where  $\ln$  is the natural logarithm,  $L$  is the likelihood function, and  $k$  is the number of parameters in the model. AIC favors a small residual error, but penalizes additional predictors that over-fit a model. In our case, a variable would stay in the model if the coefficient was significantly different than zero, and if the AIC of that model was lowered by more than 10 points [34]. Model fitting was complete once no additional variables remained, or if additional variables did not meaningfully reduce the AIC. Root mean square error ( $RMSE = \sqrt{\frac{\sum_{i=1}^n (\hat{y}_i - y_i)^2}{n}}$ ; (RMSE)), mean bias ( $Mean\ Bias = \frac{1}{n}(\sum \hat{y}_i - y_i)$ ), and the adjusted  $R$ -squared value ( $R^2_{adj} = \frac{\frac{SS_{res}}{n-k-1}}{\frac{SS_{tot}}{n-1}}$ ; ( $R^2$ )) were calculated and assessed to compare model performance.

After the model with only fixed effects was established, random effects using treatment, compartment nested within treatment, and plot nested within compartment nested within treatment were considered as a non-linear mixed effects model (NLME). The GNLS and NLME models were compared by assessing the difference in the AIC of adding random effects,  $R^2$ , mean bias, and the RMSE of predicted diameter growth. Treatment is added as a random effect, due to it being a discrete variable with seven levels (six treatments and a control).

As Weiskittel et al. [31] pointed out, when the assumption of constant variance is violated, a power variance function of the initial diameter can be included, which gives less influence to trees with larger initial diameters. This was used in both the GNLS and NLME models. The power variance function is defined as  $s^2(v) = |v|^{2t}$ , where  $s^2v$  is the variance function evaluated at  $v$ ,  $v$  is the variance covariate, and  $t$  is the variance function coefficient [31,32]. An assessment of the residual plot of fitted values confirmed no trends in the residuals.

The NLME model was also compared to the 10-year diameter growth model for black spruce over 12.7 cm DBH, developed by Deo & Froese [25] as a part of their redevelopment of the equations for large trees used in the Lake States Variant of FVS. Discrepancies currently exist over proper coefficients used in the work of Deo & Froese, and those implemented into FVS [35]. Therefore, the entire set of possible predictor variables used by Deo & Froese to model the diameter increment for all Lake States species were considered, and the resultant re-specified model was fit to the data from the Compartment Study. Using forward stepwise regression and the 'leaps' package [36], variables were selected that resulted in the best fitting model using the entire Compartment Study dataset, which included tree diameters as small as 9.1 cm, instead of the 12.7 cm minimum used in the original modeling by Deo & Froese. To overcome the uncompact crown ratio (total height of crown from crown base to total tree height) not being measured in the Compartment Study, it was predicted using the equation in FVS described by Dixon and Keyser [24].

The full range of diameters in the dataset (12.7 cm and greater) were used in comparing the model performances of the GNLS, NLME, and refit Deo & Froese models. Fit statistics (RMSE and mean bias) were compared to assess the better fitting model. While the equations for other species have been implemented into FVS, the black spruce equation has yet to be implemented. Therefore, comparisons will be made to the refit Deo & Froese model, and referred to as such, rather than the FVS model.

### 3. Results

A large range of stand conditions at the plot level—both before (Table 1) and after (Table 2) the initial treatment—and individual tree level (Table 3) existed in each treatment. However, stand conditions prior to initial treatment were not significantly different among treatments (degree of freedom,  $df = 6$ ,  $p > 0.05$ ).

**Table 1.** Mean, standard deviation (SD), and range of site index and age in six silvicultural treatments and the control in 1948 on the Big Falls Experimental Forest in northern Minnesota, USA.

Treatment	Number of Plots	Site Index (Ht in m at 100 years)			Age (years)			Basal Area (m <sup>2</sup> ha <sup>-1</sup> )			Trees (Trees ha <sup>-1</sup> )		
		Mean	SD	Range	Mean	SD	Range	Mean	SD	Range	Mean	SD	Range
Thinning	26	12.8	2.1	9.1–15.2	140.0	37.9	90–180	30.3	4.4	21.5–36.6	2125	456.4	1334–3163
Shelterwood	30	16.2	1.5	15.2–18.3	113.3	36.5	70–160	30.0	4.7	17.6–38.0	1613	426.5	618–2446
CC strips	48	13.6	2.4	9.1–18.3	134.6	14.3	100–150	28.6	6.0	12.5–39.0	1725	524.6	717–2866
CC patches	43	12.8	1.5	9.1–15.2	119.1	44.0	70–180	27.4	5.9	16.3–37.5	1927	423.0	988–2496
Group sel.	37	15.0	1.3	12.2–18.3	98.4	33.9	70–180	30.5	5.6	16.0–38.6	1921	428.0	840–2669
ST sel.	30	13.4	2.0	9.1–15.2	117.3	27.3	70–150	27.2	6.4	15.4–39.9	1753	526.8	642–2916
Control	23	13.1	2.8	9.1–18.3	106.1	27.3	70–130	25.8	6.5	10.7–33.7	1780	381.3	1013–2570

Acronyms: CC—Clearcut; sel.—Selection system; ST—Single-tree; Ht—Height; SD—Standard deviation.

**Table 2.** Mean, standard deviation (SD), and range of post-treatment density measures in six silvicultural treatments and the control in 1950 on the Big Falls Experimental Forest in northern Minnesota, USA.

Treatment	Number		Basal Area (m <sup>2</sup> ha <sup>-1</sup> )			Trees (Trees ha <sup>-1</sup> )		
	Plots	Trees	Mean	SD	Range	Mean	SD	Range
Thinning	26	1425	21.9	2.9	16.3–26.5	1443	277.3	964–2026
Shelterwood	30	423	11.8	2.5	6.9–17.4	493	105.0	297–717
CC strips <sup>1</sup>	37	2396	28.0	6.2	12.5–39.0	1718	566.6	717–2866
CC patches <sup>1</sup>	27	1994	28.1	5.3	17.9–37.5	1920	435.9	988–2496
Group sel.	25	1161	20.1	3.4	13.0–27.2	1247	286.6	667–1705
ST sel.	30	1254	17.5	5.1	9.8–32.4	1111	336.8	395–1680
Control	23	1578	25.8	6.5	11.4–33.7	1780	381.3	1013–2570

<sup>1</sup> Only plots that were entirely uncut in the original treatment were included.

**Table 3.** Mean, range, and standard deviation (SD) of variables for the diameter growth model of all trees in the dataset (9.1 cm and greater).

Variable	<i>n</i>	Mean	SD	Range
Tree	10,231			
DBH <sup>1</sup> (cm)		13.7	3.3	9.1–32.5
BAL <sup>2</sup> (m <sup>2</sup> ha <sup>-1</sup> )		14.8	8.3	0–38.8
CP <sup>3</sup>		0.700	0.459	0–1
0	3079			
1	7157			
Plot	198			
SI <sup>4</sup> (m)		13.8	2.29	9.1–18.3
BA <sup>5</sup> (m <sup>2</sup> ha <sup>-1</sup> )		21.9	7.45	6.9–39.0

<sup>1</sup> DBH: Diameter at breast height; <sup>2</sup> BAL: Plot basal area of trees larger than the subject tree; <sup>3</sup> CP: 1 for dominant and codominant trees; 0 for intermediate and suppressed trees; <sup>4</sup> SI: Site index in total height at 100 years; <sup>5</sup> BA: Basal area.

Model fitting for the GNLS and NLME equations resulted in six fixed effects, as shown in Equation (2).

$$\Delta DBH = \exp(\beta_0 + \beta_1 \log(DBH + 1) + \beta_2 DBH^2 + \beta_3 \log(SI - 1.37) + \beta_4 \frac{BAL^2}{\log(DBH+5)} + \beta_5 \sqrt{BA} + \beta_6 CP) + \varepsilon_a \quad (2)$$

After fitting the GNLS model, nested random effects were added in fitting the NLME model. Plot nested within the compartment nested within the treatment resulted in the best model fit (AIC: 19,258) (Equation (3)). The final NLME model improved the coefficient of determination ( $R^2$ ) by 51% from 0.2056 to 0.3114 over the GNLS model. The RMSE decreased 10% from 0.6772 to 0.6104 cm. Parameter estimates and their standard errors are in Table 4. Fit statistics for the final 10-year diameter growth models are in Tables 5 and 6. The final mixed effects model form was:

$$\Delta DBH = \exp(\beta_0 + b_{ijk} + \beta_1 \log(DBH + 1) + \beta_2 DBH^2 + \beta_3 \log(SI - 1.37) + \beta_4 \frac{BAL^2}{\log(DBH + 5)} + \beta_5 \sqrt{BA} + \beta_6 CP) + \epsilon_a \tag{3}$$

where  $b_{ijk}$  is a unique intercept term added to  $\beta_0$  for each plot nested within the compartment and treatment.

**Table 4.** Coefficients (Coef.) and standard errors (SE) for the generalized nonlinear least squares (GNLS) and non-linear mixed effects model (NLME) models predicting ten-year diameter growth in lowland black spruce on the Big Falls Experimental Forest in northern Minnesota, USA.

Parameter	Associated Term	GNLS		NLME	
		Coef.	SE	Coef.	SE
B <sub>0</sub>		-1.6827	0.1885	-0.6041	0.2558
B <sub>1</sub>	log(DBH + 1)	0.7777	0.0869	0.3673	0.0865
B <sub>2</sub>	DBH <sup>2</sup>	-0.0015	0.0002	-0.0012	0.0002
B <sub>3</sub>	log(SI - 1.37)	0.4444	0.0237	0.3611	0.0703
B <sub>4</sub>	BAL <sup>2</sup> (log(DBH + 5)) <sup>-1</sup>	-0.0007	0.0001	-0.0011	0.0001
B <sub>5</sub>	BA <sup>1/2</sup>	-0.1656	0.0075	-0.1303	0.0225
B <sub>6</sub>	CP	0.1587	0.0126	0.2047	0.0122

**Table 5.** Fit statistics (root mean square error (RMSE) and mean bias) and predicted and observed ten-year diameter at breast height (DBH) change values by treatment for the non-linear mixed effects model (NLME) and re-fitted Deo & Froese [25] ten-year diameter growth models for black spruce.

Treatment	RMSE (cm)		Mean Bias (cm)		Ten-Year DBH Change (cm)		
	NLME	Deo & Froese	NLME	Deo & Froese	Observed	NLME	Deo & Froese
All treatments	0.6104	0.6849	0.0054	-0.1469	1.536	1.539	1.357
Shelterwood	0.8345	0.9853	0.0047	-0.3036	2.438	2.449	2.141
ST sel.	0.6807	0.7884	-0.0074	-0.2310	1.790	1.789	1.565
Group sel.	0.6547	0.7121	-0.0018	-0.1445	1.751	1.752	1.609
Thinning	0.5697	0.5983	-0.0437	-0.1305	1.536	1.543	1.456
CC strips	0.5932	0.6750	0.0046	-0.2399	1.413	1.414	1.170
CC patches	0.5490	0.6127	0.0083	-0.1319	1.307	1.312	1.171
Control	0.5804	0.6514	0.0632	-0.1271	1.410	1.415	1.225

**Table 6.** Fit statistics for the generalized nonlinear least squares (GNLS) and non-linear mixed effects model (NLME) equations (Akaike Information Criterion (AIC) and adjusted R<sup>2</sup>) and root mean square error (RMSE) for the generalized non-linear least squares (GNLS), non-linear mixed effects (NLME), and re-fitted Deo & Froese [25] equations predicting 10-year diameter growth of black spruce.

Formula	AIC	R <sup>2</sup>	RMSE (cm)
GNLS	20,360	0.2047	0.6772
NLME	19,258	0.3113	0.6104
Deo & Froese	35,686	0.1352	0.6849

Refitting the model of Deo & Froese resulted in all but two of their independent variables being used to predict diameter increment (Equation (4)). The variables  $\frac{DBH}{QMD}$  and  $\frac{DBH^2}{QMD}$  were not significant to the model:

$$\Delta DBH = \beta_0 + \beta_1 \left( \frac{1}{DBH} \right) + \beta_2 DBH + \beta_3 + DBH^2 + \beta_4 BA + \beta_5 BAL + \beta_6 CR + \beta_7 CR^2 + \beta_8 SI \tag{4}$$

The NLME model outperformed the refit model of Deo & Froese, resulting in an R<sup>2</sup> value that was 230% higher (0.3113 vs. 0.1352) and a lower RMSE (0.6104 vs. 0.6849). The GNLS model saw

mixed results, with an adjusted  $R^2$  value of 0.2047 and a lower RMSE than the refit Deo & Froese model (0.6773).

The NLME model was much better in predicting the diameter growth over the refit Deo & Froese model across all treatments (Table 5). The overall mean bias of the NLME model was 0.0054 cm, compared with  $-0.1469$  cm for the Deo & Froese refit model. The Deo & Froese refit model underestimated diameter growth consistently across all treatments. The mean of the NLME model-predicted diameter growth was nearly identical to the observed growth, at 1.536 cm, compared to the observed growth of 1.539 cm over 10 years, while the Deo & Froese refit model averaged 1.357 cm (Table 5).

For individual treatments, RMSE for the NLME model was the smallest in the two clearcut (0.5932 and 0.5490 cm) and thinning treatments (0.5697), and largest in the shelterwood treatment (0.8345 cm). The mean bias was the smallest in the group selection method ( $-0.0018$  cm) and largest in the thinning treatment. The model overpredicted diameter growth slightly in the shelterwood and clearcut methods, and underpredicted diameter growth in the selection methods and the thinning (Table 5).

#### 4. Discussion

Ten-year diameter growth varied between treatments. The shelterwood treatment had the greatest diameter growth, likely a factor of it benefiting from increased available resources, due to having the lowest residual BA and TPA of all treatments after the initial treatment (Table 3). The higher intensity of cutting resulted in greater growing space for residual trees in this treatment. Both selection treatments had the next highest average diameter growth, and they correspondingly had the next lowest residual BA. This pattern continued for the thinning treatment. Notably, plots that were re-measured in 1960 in the clearcut treatments were those that were not harvested in the initial 1950 treatment. Plots in patches or strips that were harvested were not re-measured, due to the immature size class of regeneration. The harvest area during the initial treatment in the clearcut strips or patches may have been as close as a few meters from trees on the outer portions of unharvested plots, based on the visual evidence of treatments and the cutting cycles of the experiment (Figure 1). Girona et al. [8] documented that trees at the edge of skidding trails showed significantly increased growth compared to trees in the interior of a stand. In future studies, location relative to harvest strips and patches could be assessed for their impact on diameter growth.

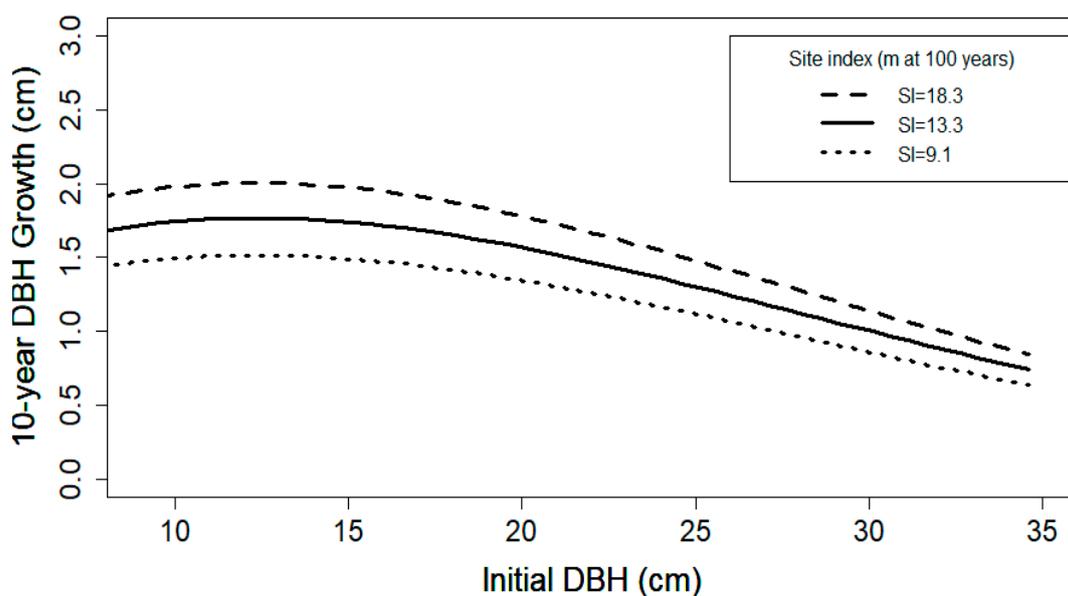
We adapted the Hann [22] model in as simple a matter as possible using two frameworks. First, we manually added basic variables (e.g., initial diameter), and progressed by adding more complex variables (Table 4). Second, we used AIC to balance the model performance with the model complexity. Fitting the diameter growth model by adapting the model of Hann [22] and manually adding variables resulted in fit statistics ( $R^2$  and RMSE) that were comparable to other modeling studies of diameter growth [22,23,25,32]. Using the power variance structure by weighting the variance for trees with larger diameters was effective in overcoming the non-constant variance to reduce the bias introduced by large trees. Stand age was tested as a possible independent variable, but this did not meaningfully reduce AIC. Age was not a factor in previous fittings using this model [22,32], or in Subedi and Sharma's [23] model fitting for black spruce in Ontario, Canada. Additionally, including age as a predictor variable may limit the model's applicability to stands where age is not measured or are uneven-aged.

Adding random effects (i.e., the NLME model) after fitting the model with all fixed effects (i.e., the GNLS model) was successful in improving the model performance, likely due to the variety of stand conditions in lowland black spruce. The method of first adding the treatment, and then the compartment nested within treatment, and finally the plot nested within the compartment nested within the treatment, was logical in terms of sequentially increasing the model complexity. Adding the compartment as a nested random effect with treatment was particularly effective in improving the model performance through reducing AIC. Compartments ranged in size from 2.3 to 3.8 hectares, and they were located within about two kilometers of one another. However, black spruce can grow on

a variety of sites with characteristics that can change even over short distances, including on this study. Site and environmental factors that were not measured, such as peat depth, water table level, soil moisture, or pH may help explain the additional variability that is not captured in the model [19,37]. This could explain the success of adding random effects at any level (i.e., treatment, compartment, and/or plot).

The NLME model outperformed the refit Deo & Froese model across treatments, and the model performance varied slightly by treatment. The higher RMSE in the shelterwood and selection treatments likely points to the difficulty in predicting the diameter across treatments that experience patchy residual areas. The shelterwood treatment aimed to leave healthy and vigorous trees, while the group and individual tree selection methods aimed to result in uneven-aged stands. The subjective nature of cutting rather than a systematic treatment, as in the clearcut treatments, likely resulted in the patchy distribution of residual trees, and variable resources.

This modeling approach fits a single growth model to all diameters in the dataset (9.1–32.5 cm), which may be more appropriate than fitting two models for large and small trees. The work by Deo & Froese [25] refit the large tree diameter growth equations (trees greater than 12.7 cm) used in the Lake States Variant of FVS. The FVS framework models diameter growth differently for large and small trees (those below 12.7 cm DBH, and those equal to or greater than 12.7 cm). Fitting a single growth model for black spruce and other slow-growing species that attain smaller diameters may be advantageous over the current approach in FVS. The diameter growth curve (Figure 3) under average stand conditions shows that diameter growth in peatland black spruce peaks around 12.7 cm. Since black spruce grows under a variety of site conditions, and maximum sizes vary largely, depending on those conditions, having separate equations for small and large trees with a transition near the peak of diameter growth for a species may not be ideal. Additionally, FVS diameter increment models for large and small trees were originally developed for the Intermountain West, where average and maximum diameters for tree species are generally greater than that of Lake States species. Fitting separate equations with a breakpoint diameter of 12.7 cm in those geographic regions may be more appropriate than in the Lake States, particularly for species with smaller maximum diameters, like black spruce.



**Figure 3.** Diameter growth of dominant and codominant trees (crown position = 1) using the non-linear mixed effects (NLME) coefficients at the maximum (18.3), mean (13.2), and minimum (9.1) site indices in average pre-treatment stand conditions (basal area = 22.0 m<sup>2</sup> ha<sup>-1</sup>, basal area in larger trees = 14.8 m<sup>2</sup> ha<sup>-1</sup>).

It is important that diameter growth models used by managers are applicable to the conditions where they are applied. This is of particular important in lowland black spruce in the Lake States, where the cover type tends to grow in pure stands, and growing conditions vary widely depending on its location and proximity to its range edges [1]. Understanding how silvicultural systems and stand- and tree-level attributes affect diameter growth and its modeling in varying geographical locations and physiological conditions is critical for managers to be able to accurately model future stand conditions and volumes.

This model fitting resulted in the same variables predicting the diameter growth, as was found with the same model for other species by Hann [22] and Weiskittel et al. [31], with the notable substitution of a crown position indicator variable for crown ratios. This substitution seems adequate, given that the crown ratio was not measured in the original study. While crown ratio as an absolute measure would be a more accurate portrayal of a tree's crown than the subjective measure of crown class, crown class may provide an alternative measurement to the crown ratio. This is of particular relevance in black spruce peatlands, where visibility in the canopy can be low, due to dense crowns and high stand densities.

The signs and values for both the GNLS and NLME models matched biological expectations for diameter growth. Positive coefficients occurred with  $\log(\text{DBH} + 1)$ ,  $\log(\text{SI} - 1.37)$ , and the crown position dummy variable, indicating diameter growth, was positively correlated with these variables. Diameter growth was negatively correlated with  $\text{BA}^{1/2}$ ,  $\text{DBH}^2$ , and  $\frac{\text{BAL}^2}{\log(\text{DBH}+5)}$ . Notably, DBH growth is strongly positively correlated with  $\log(\text{DBH} + 1)$ , and negatively correlated with  $\text{DBH}^2$ , showing that black spruce individuals with particularly large initial diameters will grow more slowly than trees with smaller diameters. This is evidenced when examining diameter growth in average stand conditions using the NLME parameters (Figure 3).

One important factor in black spruce growth that was not considered in this study is eastern spruce dwarf mistletoe. While it was not present on the study site, dwarf mistletoe is a prevalent health concern in black spruce forests in Minnesota, and more broadly, in the Lake States, and it considerably slows growth and reduces stand volumes [15,16]. Future studies in the diameter growth of black spruce could focus on the effects of mistletoe.

## 5. Conclusions

Individual-tree non-linear fixed effects (GNLS) and mixed effects (NLME) 10-year diameter growth models were adapted and fit to lowland black spruce across six silvicultural treatments. Adapting the model by Hann [22] was successful in predicting 10-year diameter growth in lowland black spruce across the breadth of treatments, resulting in similar fit statistics to other diameter growth models ( $R^2$  and RMSE). Substituting crown class for crown ratio as a predictor variable due to variable availability proved to be an effective substitution. Adding a random effect of plot nested within compartment nested within treatment in the NLME model improved its fit over the GNLS model. The GNLS and NLME modeling approach more accurately predicted diameter growth compared to the conventional approach used in FVS of using separate small and large diameter models. We recommend this approach as an improved alternative in the lowland black spruce cover type to the conventional procedures in FVS, where separate diameter growth models are used for small- and large-diameter trees.

**Supplementary Materials:** Data is published in the University of Minnesota data repository at the following URL: <http://hdl.handle.net/11299/199817>.

**Author Contributions:** B.D.A., M.B.R., and M.W.-C. developed study design. B.D.A. analyzed the data and fit growth models. M.B.R. fit growth models. B.J.P. and D.N.K. provided access to historical data records and provided information on the study history. All authors wrote the paper.

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## References

1. Viereck, L.A.; Johnston, W.F. *Picea mariana* (Mill.) B.S.P. In *Agriculture Handbook 654*; Burns, R.M., Honkala, B.H., Eds.; Silvics of North America: Volume 1—Conifers; USDA Forest Service: Washington, DC, USA, 1990; p. 877.
2. Miles, P.D. Forest Inventory EVALIDator Web-application, Version 1.6.0.03. Available online: <http://apps.fs.fed.us/Evalidator/evalidator.jsp> (accessed on 17 April 2017).
3. Minnesota Department of Natural Resources. *Minnesota’s Forest Resources 2016*; Minnesota Department of Natural Resources: Saint Paul, MN, USA, 2017.
4. Eyre, F.H. *Forest Cover Types of the United States and Canada*, 6th ed.; Society of American Foresters: Washington, DC, USA, 1980.
5. Heinselman, M.L. *Silvical Characteristics of Black Spruce (Picea Mariana)*; Lake States Forest Experiment Station, Forest Service, U.S. Dept. of Agriculture: St. Paul, MN, USA, 1957.
6. Perala, D.A. *Growth and Yield of Black Spruce on Organic Soils in Minnesota*; Research Paper NC-56.; USDA Forest Service, North Central Forest Experiment Station: St. Paul, MN, USA, 1971.
7. Vincent, M.; Krause, C.; Zhang, S.Y. Radial growth response of black spruce roots and stems to commercial thinning in the boreal forest. *Forestry* **2009**, *82*, 557–571. [[CrossRef](#)]
8. Girona, M.M.; Morin, H.; Lussier, J.M.; Walsh, D. Radial growth response of black spruce stands ten years after experimental shelterwoods and seed-tree cuttings in boreal forest. *Forests* **2016**, *7*, 240. [[CrossRef](#)]
9. Pamerleau-Couture, É.; Krause, C.; Pothier, D.; Weiskittel, A. Effect of three partial cutting practices on stand structure and growth of residual black spruce trees in north-eastern Quebec. *Forestry* **2015**, *88*, 471–483. [[CrossRef](#)]
10. Groot, A.; Hökkä, H. Persistence of suppression effects on peatland black spruce advance regeneration after overstory removal. *Can. J. For. Res.* **2000**, *30*, 753–760. [[CrossRef](#)]
11. Thorpe, H.C.; Thomas, S.C. Partial harvesting in the Canadian boreal: Success will depend on stand dynamic responses. *For. Chron.* **2007**, *83*, 319–325. [[CrossRef](#)]
12. Baker, F.A.; O’Brien, J.G.; Mathiasen, R.; Ostry, M.E. *Eastern Spruce Dwarf Mistletoe*; USDA Forest Service, Northeastern Area: Newtown Square, PA, USA, 2006.
13. Anderson, R.L. The Black Spruce Dwarf Mistletoe in Minnesota. Master’s Thesis, University of Minnesota, Minneapolis, MN, USA, June 1949.
14. LeBarron, R.K. Light cutting in black spruce is practicable. *J. For.* **1945**, *43*, 486–489.
15. Baker, F.; Hansen, M.; Shaw, J.D.; Mielke, M.; Shelstad, D. The incidence of dwarf mistletoe in Minnesota black spruce stands detected by operational inventories. *North. J. Appl. For.* **2012**, *29*, 109–112. [[CrossRef](#)]
16. Baker, F.A.; Knowles, K.R. Case study: 36 years of dwarf mistletoe in a regenerating black spruce stand in Northern Minnesota. *North. J. Appl. For.* **2004**, *21*, 150–153.
17. Anderson, R.L.; Kaufert, F.H. *The Control of Dwarf Mistletoe on Black Spruce*; Minnesota Agricultural Experiment Station: Saint Paul, MN, USA, 1953.
18. Coates, K.D.; Steventon, J.D. Patch retention harvesting as a technique for maintaining stand level biodiversity in forests of north central British Columbia. In *Proceedings of the Innovative Silviculture Systems in Canada’s Boreal Forests*; Bamsey, C.R., Ed.; Clear Lake Ltd.: Edmonton, AB, Canada, 1995; pp. 102–106.
19. LeBarron, R.K. *Silvicultural Management of Black Spruce in Minnesota*; Lake States Forest Experiment Station, Forest Service, U.S. Dept. of Agriculture: Washington, DC, USA, 1948; Volume 791.
20. Schantz-Hansen, T. Preliminary Observations on the Use of Clear Cut Strips in Handling Black Spruce. *J. For.* **1931**, *29*, 1168–1172.
21. Fox, G.D.; Kruse, G.W. A yield table for well-stocked stands of black spruce in northeastern Minnesota. *J. For.* **1933**, *37*, 565–567.

22. Hann, D.W.; Marshall, D.D.; Hanus, M.L. *Equations for Predicting Height-to-Crown Base, 5-Year Diameter Growth Rate, 5-Year Height-Growth Rate, 5-Year Mortality Rate, and Maximum Size-Density Trajectory for Douglas-Fir and Western Hemlock in the Coastal Region of the Pacific Northwest*; Oregon State University: Corvallis, OR, USA, 2003; Volume 40.
23. Subedi, N.; Sharma, M. Forest Ecology and Management Individual-tree diameter growth models for black spruce and jack pine plantations in northern Ontario. *For. Ecol. Manag.* **2011**, *261*, 2140–2148. [[CrossRef](#)]
24. Dixon, G.E.; Keyser, C.E. *USDA Forest Service. Lake States (LS) Variant Overview, Forest Vegetation Simulator*; USDA Forest Service: Fort Collins, CO, USA, 2013.
25. Deo, R.K.; Froese, R.E. Refitting the Large-Tree Diameter Growth Equations of the Lake States and Central States Variants of the Forest Vegetation Simulator. Available online: [https://www.researchgate.net/publication/328974689\\_Refitting\\_the\\_Large\\_Tree\\_Diameter\\_Growth\\_Equations\\_of\\_the\\_Lake\\_States\\_and\\_Central\\_States\\_Variants\\_of\\_the\\_Forest\\_Vegetation\\_Simulator/stats](https://www.researchgate.net/publication/328974689_Refitting_the_Large_Tree_Diameter_Growth_Equations_of_the_Lake_States_and_Central_States_Variants_of_the_Forest_Vegetation_Simulator/stats) (accessed on 1 May 2018).
26. Aaeseng, N.; Almendinger, J.; Rusterholz, K.; Wovcha, D.; Klein, T.R. *Field Guide to the Native Plant Communities of Minnesota: The Laurentian Mixed Forest Province*; Minnesota Department of Natural Resources: Saint Paul, MN, USA, 2003.
27. Adams, M.B.; Loughry, L.H.; Plaughner, L. *Experimental Forests and Ranges of the USDA Forest Service*; U.S. Dept. of Agriculture, Forest Service: Washington, DC, USA, 2004.
28. Neff, L.P. A comprehensive cutting study in swamp black spruce. *Pulp and Paper Magazine of Canada*, May 1952.
29. Minnesota Department of Conservation; USDA Forest Service. *Memorandum of Understanding between the Minnesota Department of Conservation and the Forest Service, United States Department of Agriculture Covering Conduct of Forest Management Experiments*; USDA Forest Service: Grand Rapids, MN, USA, 1948.
30. USDA Forest Service. Working Plan for Compartment Study of Cutting Methods in Swamp Black Spruce—Big Falls Experimental Forest. Unpublished work, 1948.
31. Weiskittel, A.R.; Garber, S.M.; Johnson, G.P.; Maguire, D.A.; Monserud, R.A. Annualized diameter and height growth equations for Pacific Northwest plantation-grown Douglas-fir, western hemlock, and red alder. *For. Ecol. Manag.* **2007**, *250*, 266–278. [[CrossRef](#)]
32. R Core Team. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. Available online: <https://www.r-project.org/> (accessed on 1 May 2018).
33. Pinheiro, J.; Bates, D.; DebRoy, S.; Sarkar, D. R Core Team Linear and Nonlinear Mixed Effects Models. Available online: <https://cran.r-project.org/package=nlme> (accessed on 1 May 2018).
34. Burnham, K.P.; Anderson, D.R. Multimodel inference: Understanding AIC and BIC in model selection. *Sociol. Methods Res.* **2004**, *33*, 261–304. [[CrossRef](#)]
35. Smith-Mateja, E.; (USDA Forest Service, Grants Pass, OR, USA). Personal communication, 2018.
36. Lumley, T. Based on R Code by A. M. Leaps: Regression Subset Selection, R Package Version 3.0. Available online: <https://cran.r-project.org/package=leaps> (accessed on 1 May 2018).
37. Drobyshev, I.; Simard, M.; Bergeron, Y.; Hofgaard, A. Does soil organic layer thickness affect climate-growth relationships in the black spruce boreal ecosystem? *Ecosystems* **2010**, *13*, 556–574. [[CrossRef](#)]

