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Article

Regional Models of Diameter as a Function of Individual Tree Attributes, Climate and Site Characteristics for Six Major Tree Species in Alberta, Canada

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Abstract: We investigated the relationship of stem diameter to tree, site and stand characteristics for six major tree species (trembling aspen, white birch, balsam fir, lodgepole pine, black spruce, and white spruce) in Alberta (Canada) with data from Alberta Sustainable Resource Development Permanent Sample Plots. Using non-linear mixed effects modeling techniques, we developed models to estimate diameter at breast height using height, crown and stand attributes. Mixed effects models (with plot as subject) using height, crown area, and basal area of the larger trees explained on average 95% of the variation in diameter at breast height across the six species with a root mean square error of 2.0 cm (13.4% of mean diameter). Fixed effects models (without plot as subject) including the Natural Sub-Region (NSR) information explained on average 90% of the variation in diameter at breast height across the six species with a root mean square error equal to 2.8 cm (17.9% of mean diameter). Selected climate variables provided similar results to models with NSR information. The inclusion of nutrient regime and moisture regime did not significantly improve the predictive ability of these models.

Keywords: diameter-height models; non-linear mixed-effects; crown; basal area; climate variables; natural sub-region

1. Introduction

Accurate measurements of diameter and height are of critical importance to forest managers and practitioners in the decision-making process, since these tree attributes allow the indirect estimation of stem volume, biomass, and site index. The estimation of stem diameter and height for individual trees plays a pivotal role in the development of reliable growth and yield curves [1], and in the development of detailed forest inventories [2].

While field measurements of diameter at breast-height (DBH) are relatively easy and inexpensive, the traditionally more challenging task of height measurement has been transformed by light detection and ranging (LiDAR) technology [3]. The information collected using LiDAR has already been widely used to estimate: tree height, height and diameter distribution, leaf area index, biomass and crown attributes of individual trees [4-8]. With the potential to rapidly measure tree height and other attributes via remote sensing, the focus is now on improving the simple linear models available to derive stem diameter from height, crown and stand attributes [9].

The challenge in developing widely applicable height estimation models is to effectively represent the influence of tree-, stand-, site- and regional-level variables. Numerous studies have already shown that the allometric relationship between diameter and height is influenced by factors such as crown length, stand density and site index [10-12]. Edaphic and climatic variables have been shown to improve the estimation of forest growth projections [13], and may also influence the tree allometry, including height-diameter relationships.

In Alberta, edaphic and climatic site characteristics can be obtained from: (1) ecoregion classification such as the Natural Regions of Alberta, which are ecological units geographically defined by vegetation, soil and physiographic features which are influenced by climate, topography and geology [14]; (2) spatial climate models such as ClimateWNA that provide climate data for a given location based on latitude, longitude and elevation [15]; and (3) moisture and nutrient regimes information that is available from inventory surveys.

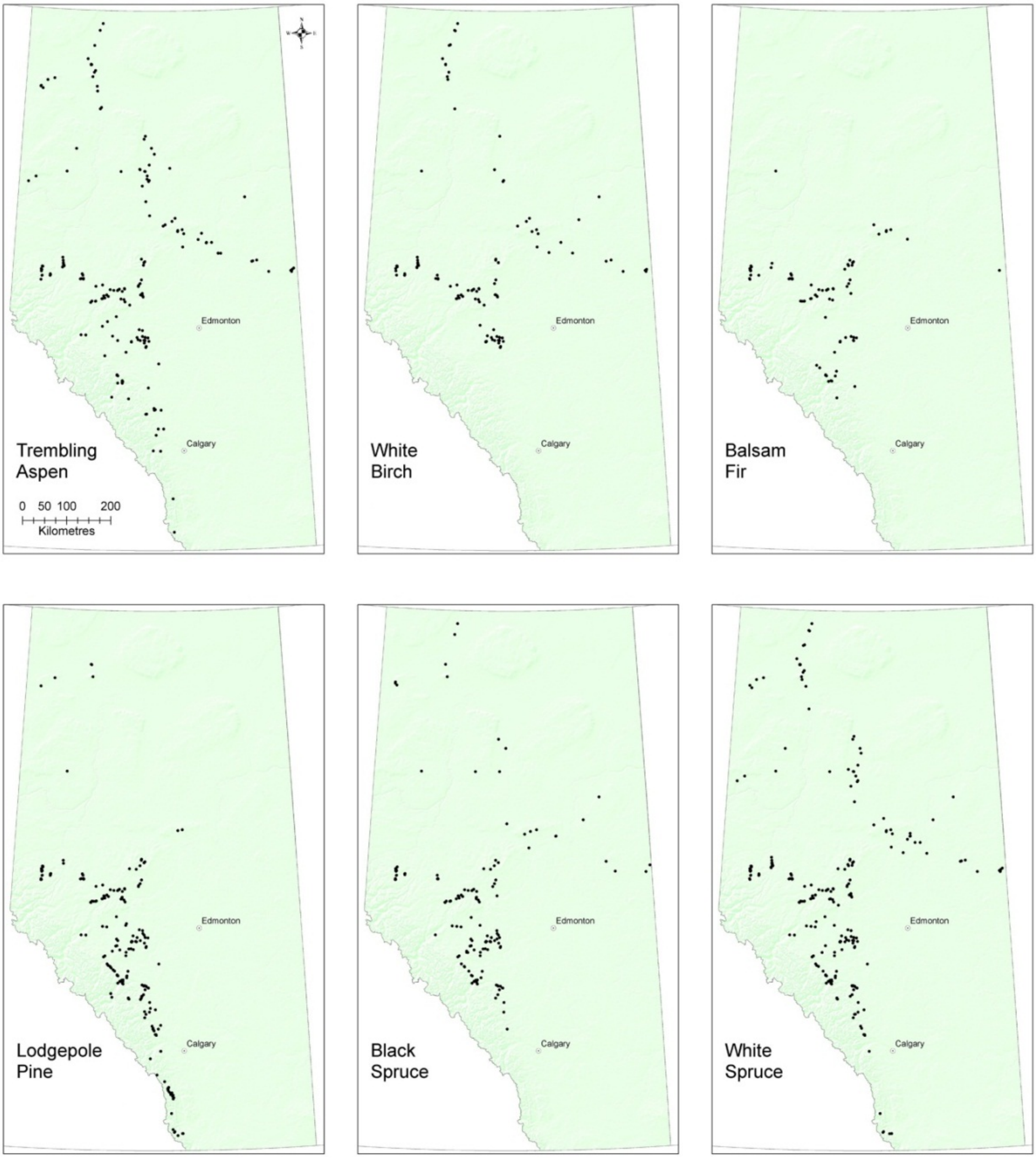
Our main objective was to develop non-linear diameter models using ground-measured height, crown, basal area and other attributes (e.g., climate, nutrient and moisture regime) for six major tree species in Alberta, Canada.

2. Materials and Methods

2.1. Study Data Description

The data used for this study comes from the Alberta Government's Permanent Sample Plots (PSPs) located across the province of Alberta (Figure 1). The tree species were selected based on the number of sampled trees available by excluding those species with less than 1000 observations. The selected species are: two broadleaves including trembling aspen (*Populus tremuloides* Michx.) and white birch (*Betula papyrifera* Marsh.); and four conifers including balsam fir (*Abies balsamea* (L.) Mill.), lodgepole pine (*Pinus contorta* Dougl.), black spruce (*Picea mariana* (Mill.) B.S.P.), and white spruce (*Picea glauca* (Moench) Voss).

Figure 1. Location of individual Permanent Sample Plot (PSP) containing the various species. Note: each map shows the location of plots containing the labelled species.



According to the '2005 PSP Field Procedure Manual' [16], height to live crown is that point that divides a portion of the tree that is continuously branched from another part that has sporadic or no branching. For broadleaf trees the live crown starts at the lowest leaves level and not at the branch level. Crown width measurements are taken in the four cardinal directions (*i.e.*, North, West, South and East) at the widest portion of the foliage for each direction by looking up from the base of the tree. Crown attributes such as crown area (CA), crown volume (CV), and crown surface area (CSA) were then calculated assuming a prolate ellipsoid shape for the broadleaves, and a conical shape for the conifers. Crown radii were not measured for each tree in the plot; therefore crown attributes of competing vegetation could not be used as an estimate of competition.

In order to quantify the effect of competition, we calculated: basal area per hectare (BA), number of trees per hectare (TN), and basal area of the larger trees per hectare (BALT). BALT is the basal area sum of each tree larger than the subject tree (within the plot). For each species and PSP only the last available measurement was used for the analysis. Table 1 for the broadleaves and Table 2 for the conifers, provide basic statistical information (e.g., mean and standard deviation) for a number of representative variables such as plot size, DBH, height, and crown and stand attributes.

Table 1. Basic statistical information of selected variables for each broadleaf species.

Species	**Variable**	**Minimum**	**Mean**	**Maximum**	**Standard Deviation**
	Plots size (ha)	0.02	0.13	0.20	0.05
Trembling aspen (Aw)	DBH (cm)	0.1	24.0	74.8	13.4
PSPs: 194	HT (m)	1.3	20.3	37.2	7.4
Observations:	CR (m)	0.1	1.8	6.0	0.9
2791	CL (m)	0.1	5.7	16.5	2.6
	CA (m^2)	0.1	13.5	112.0	13.3
	BA (m^2 ha^{-1})	6.8	39.8	94.2	12.6
	BALT (m^2 ha^{-1})	0.0	23.0	94.2	14.6
	Plot size (ha)	0.02	0.14	0.20	0.05
White birch (Bw)	DBH (cm)	0.2	9.3	40.4	6.8
PSPs:113	HT (m)	1.3	9.7	26.5	5.3
Observations:	CR (m)	0.1	1.4	5.2	0.7
1351	CL (m)	0.1	5.1	15.4	3.1
	CA (m^2)	0.1	7.7	84.9	7.4
	BA (m^2 ha^{-1})	6.8	38.1	106.8	12.6
	BALT (m^2 ha^{-1})	2.4	36.2	106.8	13.2

Table 2. Basic statistical information of selected variables for each conifer species.

Species	Variable	Minimum	Mean	Maximum	Standard Deviation
	Plot size (ha)	0.04	0.13	0.20	0.05
Balsam fir (Fb)	DBH (cm)	0.1	11.0	44.7	8.2
PSPs: 88	HT (m)	1.3	9.7	29.2	6.5
Observations:	CR (m)	0.1	1.2	3.0	0.5
1507	CL (m)	0.1	5.7	24.5	4.0
	CA (m^2)	0.1	5.3	28.7	4.3
	BA (m^2 ha^{-1})	10.3	41.6	106.8	12.9
	BALT (m^2 ha^{-1})	0.0	38.4	106.5	14.1
	Plot size (ha)	0.02	0.09	0.20	0.05
Lodgepole pine (Pl)	DBH (cm)	0.3	21.2	52.5	8.2
PSPs: 230	HT (m)	1.4	19.2	34.4	5.7
Observations:	CR (m)	0.1	1.2	3.5	0.5
5450	CL (m)	0.1	5.4	19.2	2.4
	CA (m^2)	0.1	5.4	39.6	4.8
	BA (m^2 ha^{-1})	1.1	45.3	125.0	15.0
	BALT (m^2 ha^{-1})	0.0	24.5	107.0	14.9
	Plot size (ha)	0.02	0.09	0.20	0.05
Black spruce (Sb)	DBH (cm)	0.3	13.6	44.3	6.3
PSPs: 155	HT (m)	1.4	12.4	32.0	5.0
Observations:	CR (m)	0.1	1.0	3.5	0.4
2380	CL (m)	0.3	7.0	23.8	4.1
	CA (m^2)	0.1	3.9	38.8	3.3
	BA (m^2 ha^{-1})	0.7	44.2	125.0	20.6
	BALT (m^2 ha^{-1})	0.0	34.6	124.1	19.0
	Plot size (ha)	0.02	0.13	0.20	0.06
White spruce (Sw)	DBH (cm)	0.2	19.4	78.2	11.9
PSPs: 249	HT (m)	1.3	15.8	39.1	8.1
Observations:	CR (m)	0.1	1.4	5.2	0.6
4450	CL (m)	0.2	9.1	33.2	5.1
	CA (m^2)	0.1	7.7	84.1	6.7
	BA (m^2 ha^{-1})	1.1	41.9	94.2	11.6
	BALT (m^2 ha^{-1})	0.0	31.3	89.4	15.2

We also calculated a number of selected climate variables using the spatial climate model ClimateWNA [17] that provided monthly data for each site based on latitude, longitude and elevation [15]. For the climate normal period 1971–2000, we calculated climate data for five representative climate variables including: MSP = Mean annual Summer (May to September) Precipitation (mm); AH:M = Annual Heat:Moisture index (*i.e.*, (Mean Annual Temperature + 10)/(Mean Annual Precipitation/1000)); SH:M = Summer Heat:Moisture index (*i.e.*, (Mean Warmest Month Temperature)/(MSP/1000)); DD > 5 = Degree-Days above 5 °C (*i.e.*, growing degree-days); and CMD = Hargreaves Climatic Moisture Deficit [18]. Table 3 provides basic statistical information (e.g., mean and standard deviation) for each climate variable.

Table 3. Basic statistical information of selected climate variables for each tree species.

Species	Variable	Minimum	Mean	Maximum	Standard Deviation
Trembling aspen (Aw)	MSP (mm)	226.0	362.5	485.0	67.1
	AH:M	14.5	21.7	25.6	1.6
	SH:M	23.9	43.5	72.7	11.4
	DD > 5	361.0	1188.8	1423.0	130.3
	CMD	2.0	118.4	234.0	61.0
White birch (Bw)	MSP (mm)	226.0	384.4	493.0	67.1
	AH:M	17.7	21.4	25.6	1.1
	SH:M	23.9	40.7	73.1	11.4
	DD > 5	361.0	1182.8	1677.0	128.2
	CMD	22.0	100.0	262.0	58.0
Balsam fir (Fb)	MSP (mm)	310.0	426.1	511.0	31.4
	AH:M	14.1	19.9	25.6	1.7
	SH:M	25.7	33.7	54.6	3.9
	DD > 5	640.0	1105.5	1385.0	146.3
	CMD	0.0	54.5	195.0	24.4
Lodgepole pine (Pl)	MSP (mm)	251.0	422.4	575.0	36.5
	AH:M	8.9	19.2	25.3	2.5
	SH:M	22.3	33.2	63.9	5.1
	DD > 5	640.0	1049.5	1891.0	197.1
	CMD	0.0	61.2	261.0	41.1
Black spruce (Sb)	MSP (mm)	229.0	415.9	575.0	48.8
	AH:M	14.5	20.3	25.1	1.5
	SH:M	23.6	35.1	70.4	7.5
	DD > 5	640.0	1100.0	1549.0	126.4
	CMD	2.0	69.1	224.0	40.4
White spruce (Sw)	MSP (mm)	226.0	387.5	575.0	69.0
	AH:M	14.1	20.6	25.6	2.0
	SH:M	23.6	39.4	73.1	11.7
	DD > 5	361.0	1117.7	1891.00	160.0
	CMD	0.0	90.5	262.0	63.1

2.2. Model Selection

During the preliminary analysis we screened several non-linear candidate equations to investigate the relationship between diameter and height. We compared the models using several criteria such as the coefficient of determination (R^2), the root mean squared error (RMSE), and the Akaike's information criterion (AIC), which quantifies the tradeoff between bias and variance in model construction. The following models fitted the data well:

$$[\,DBH = \beta_0 (HT - 1.29)^{\beta_1}\,] \tag{1}$$

$$[\,DBH = \beta_0 (HT - 1.29)^{\beta_1} * \beta_2^{(HT-1.29)}\,] \tag{2}$$

DBH was measured at 1.3 m; however we decided to also include in the models those trees that are 1.3 m tall by using height minus 1.29 m for the analysis.

The relationship between diameter (*i.e.*, DBH) and crown attributes (*i.e.*, crown radius, crown length, crown area, crown volume, crown surface area) was then tested using the following model selected during preliminary analysis:

$$[DBH = \beta_0 (CrownAttribute)^{\beta_1}] \quad (3)$$

Analysis indicated that crown volume and crown length were the best predictors (lower AIC) of diameter for the six tree species. However, considering that crown area also performed well, and is easily determined from LiDAR or aerial photos we decided to use this variable in subsequent analysis. Thus crown area (CA) was added to Equations (1) and (2) as follows:

$$[DBH = \beta_0 (HT - 1.29)^{\beta_1} * CA^{\beta_3}] \quad (4)$$

$$[DBH = \beta_0 (HT - 1.29)^{\beta_1} * \beta_2^{(HT-1.29)} * CA^{\beta_3}] \quad (5)$$

Preliminary analysis also included F-ratio tests [19] to compare Equation (1) with Equation (2); and Equation (4) with Equation (5). The results indicated that Equation (4) was the best model (lowest AIC) for trembling aspen and white birch; and Equation (5) was the best model (lowest AIC) for balsam fir, lodgepole pine, black spruce and white spruce.

During the preliminary analysis we also included stand and tree attributes such as basal area per hectare (BA), the number of trees per hectare (TN), and, at the tree level, basal area of the larger trees per hectare (BALT) into the model. The results indicated that BALT had the highest predictive ability (lowest AIC). F-ratio tests were then carried out to investigate if the inclusion of BALT improved the overall predictive ability (lower AIC) compared to models without the stand attribute. The results provided evidence that including BALT significantly improved the model fit and was therefore included in the base models as follows:

$$[DBH = \beta_0 * (HT - 1.29)^{\beta_1} * CA^{\beta_3} * (1 + BALT)^{\beta_4}] \quad (6)$$

$$[DBH = \beta_0 * (HT - 1.29)^{\beta_1} * \beta_2^{(HT-1.29)} * CA^{\beta_3} * (1 + BALT)^{\beta_4}] \quad (7)$$

2.3. Natural Sub-Region, Moisture and Nutrient Regimes, and Climate

Natural Sub-Region (NSR) [14] and moisture and nutrient regimes [20] were separately added to the models using indicator variables (*i.e.*, $z_i * d_i$; where d_i is the indicator variable 1 if NSR, 0 otherwise, and z_i is the NSR parameter) [19]. The NSRs include the Central Mixedwood, the Dry Mixedwood, the Lower Boreal Highlands, the Lower Foothills, the Montane, the Northern Mixedwood, the Subalpine, and the Upper Foothills [21]. The moisture regimes (*i.e.*, 2–9) were grouped into low, medium, and high levels of moisture (*i.e.*, Low = 2, 3, and 4; Medium = 5 and 6; High = 7, 8, and 9), and the nutrient regimes (*i.e.*, 1–5) were grouped into low, medium, and high levels (*i.e.*, Low = 1 and 2; Medium = 3; High = 4 and 5).

For trembling aspen and white birch the equation tested is:

$$[DBH = (\beta_0 + z_i * d_i) * (HT - 1.29)^{\beta_1} * CA^{\beta_3} * (1 + BALT)^{\beta_4}] \quad (8)$$

For balsam fir, lodgepole pine, black spruce and white spruce the equation tested is:

$$[DBH = (\beta_0 + z_i * d_i) * (HT - 1.29)^{\beta_1} * \beta_2^{(HT-1.29)} * CA^{\beta_3} * (1 + BALT)^{\beta_4}] \quad (9)$$

F-ratio tests were then used to investigate if two or more NSRs could be grouped together, and to test if the inclusion of NSR, and moisture and nutrient regimes overall improved the predictive ability of the base model.

Then we tested the inclusion of five representative climate variables (*Clim. Var.*) such as MSP, AH:M, SH:M, DD > 5, and CMD. For trembling aspen and white birch the equation tested is:

$$[DBH = \beta_0 * (HT - 1.29)^{\beta_1} * CA^{\beta_3} * (1 + BALT)^{\beta_4} * Clim.Var.^{\beta_5}] \quad (10)$$

For balsam fir, lodgepole pine, black spruce and white spruce the equation tested is:

$$[DBH = \beta_0 * (HT - 1.29)^{\beta_1} * \beta_2^{(HT-1.29)} * CA^{\beta_3} * (1 + BALT)^{\beta_4} * Clim.Var.^{\beta_5}] \quad (11)$$

2.4. Mixed Model Analysis

In order to account for the nested sources of variability related to plot, preliminary analysis of mixed effect models including plot as a random subject in Equations (8) and (9) was carried out. For each species, best results were obtained for models with only one random parameter (b_0 added to the slope β_0). Mixed effect models with more than one random parameter either failed to converge or resulted in non-significant estimates, likely owing to the relatively small number of trees in some PSPs. These models were then tested with and without the inclusion of NSR information (*i.e.*, z_i*d_i). For trembling aspen and white birch the equations tested are:

$$[DBH = ((\beta_0 + z_i * d_i) + b_0) * (HT - 1.29)^{\beta_1} * CA^{\beta_3} * (1 + BALT)^{\beta_4}] \quad (12)$$

$$[DBH = (\beta_0 + b_0) * (HT - 1.29)^{\beta_1} * CA^{\beta_3} * (1 + BALT)^{\beta_4}] \quad (13)$$

For balsam fir, lodgepole pine, black spruce and white spruce the equations tested are:

$$[DBH = ((\beta_0 + z_i * d_i) + b_0) * (HT - 1.29)^{\beta_1} * \beta_2^{(HT-1.29)} * CA^{\beta_3} * (1 + BALT)^{\beta_4}] \quad (14)$$

$$[DBH = (\beta_0 + b_0) * (HT - 1.29)^{\beta_1} * \beta_2^{(HT-1.29)} * CA^{\beta_3} * (1 + BALT)^{\beta_4}] \quad (15)$$

Parameter estimation for both fixed-effects and mixed-effects models was completed using the NLMIXED procedure in SAS statistical package [22].

3. Results

The base model that included Ht, crown area and BALT accounted for much of the variation in DBH (R^2 from 0.858 to 0.937) and resulted in RMSE ranging from 4.6 to 2.0 cm (Table 4). Including NSR information into the base models significantly improved the model fit for all six species (Table 5). F-ratio tests indicated that grouping three NSRs (*i.e.*, Central Mixedwood, Dry Mixedwood and Northern Mixedwood) reduced AIC for trembling aspen, but grouping NSRs increased AIC for the remaining species.

The inclusion of moisture regime resulted in parameters significantly different from zero (α = 0.05) only for trembling aspen and white spruce. However, moisture regime did not improve the overall fit (resulting in higher AIC) compared to models with NSR information. Adding nutrient regime into the model again resulted in parameters significantly different from zero (α = 0.05) for trembling aspen and white spruce. Inclusion of nutrient regime improved the model fit only for trembling aspen as compared to the model with the NSR information, but not for white spruce.

Adding climate variables to the models resulted in a better fit for trembling aspen, lodgepole pine, and black spruce compared to models with NSR information (Table 6). For balsam fir there was no significant difference between the two models, and for white birch and white spruce the models with the NSRs provided slightly better fit than the models with the climate variables.

The results from the mixed model analysis indicate that by adding plot as a random subject, the overall fit of the model improved compared to fixed effect models only (Tables 7 and 8; and Figure 2). However, mixed effect models resulted in only minor improvements for models with NSR information.

Table 4. Parameters estimates (reported with standard errors) and goodness-of-fit for tree diameter modeled as a function of height, crown area, and basal area of the larger trees, for trembling aspen and white birch Equation (6); and for balsam fir, lodgepole pine, black spruce and white spruce Equation (7), as described in Section 2.2.

Spp.	β_0	β_1	β_2	β_3	β_4	R^2	RMSE cm	AIC
Aw	1.0691 (0.548)	1.0066 (0.171)	-	0.1681 (0.005)	−0.1016 (0.003)	0.883	4.567	16410
Bw	1.6998 (0.097)	0.7918 (0.021)	-	0.2339 (0.012)	−0.1262 (0.011)	0.883	2.328	6123.7
Fb	3.5636 (0.161)	0.7496 (0.274)	1.0014 (0.002)	0.1019 (0.006)	−0.1716 (0.005)	0.937	2.054	6461.5
Pl	3.3821 (0.223)	0.5803 (0.035)	1.0122 (0.002)	0.128 (0.003)	−0.08618 (0.002)	0.858	3.081	27739
Sb	3.0794 (0.155)	0.6881 (0.032)	1.0051 (0.002)	0.148 (0.004)	−0.1159 (0.142)	0.878	2.220	10558
Sw	2.2699 (0.108)	0.8587 (0.025)	0.9973 (0.001)	0.1372 (0.003)	−0.1134 (0.002)	0.924	3.269	23178

$$(pseudo)R^2 = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2} \quad ; \quad RMSE = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{n-k}} \quad ; \quad AIC = -2\ln(L) + 2k \quad ,$$

where y_i —observed values; $\hat{y}_i$ —predicted values; $\bar{y}$ —average; n—sample size; k—number of model parameters; ln(L)—logarithm of the likelihood function.

Table 5. Parameters estimates (reported with standard errors) and goodness-of-fit for tree diameter modeled as a function of height, crown area, basal area of the larger trees and natural sub-region, for trembling aspen and white birch. Equation (8); and for balsam fir, lodgepole pine, black spruce and white spruce, Equation (9), as described in Section 2.3.

Spp.	β_0	β_1	β_2	β_3	β_4	z_1	z_2	z_3	z_4	z_5	z_6	z_7	z_8	R^2	**RMSE cm**	**AIC**
						CM,DMW, NM	LF,UF	LBH	M							
Aw	1.0399 (0.053)	1.0187 (0.017)	-	0.1643 (0.005)	−0.1001 (0.003)	−0.06211 (0.022)	0.02761 (0.014)	−0.1366 (0.020)	0.2536 (0.061)	-	-	-	-	0.887	4.501	16328
						CM	DMW	LBH	LF	M	NM	SA	UF			
Bw	0.9024 (0.099)	0.7962 (0.021)	-	0.2296 (0.012)	−0.146 (0.012)	0.8119 (0.027)	1.2869 (0.075)	0.9264 (0.050)	0.9469 (0.026)	-	0.9965 (0.053)	-	1.1339 (0.097)	0.889	2.279	6071.6
Fb	2.7672 (0.121)	0.7573 (0.026)	0.9981 (0.002)	0.1082 (0.007)	−0.1613 (0.005)	0.4391 (0.054)	-	-	0.6233 (0.041)	-	-	0.9414 (0.106)	0.9634 (0.054)	0.943	1.955	6308.4
Pl	1.7948 (0.182)	0.607 (0.036)	1.0133 (0.002)	0.1322 (0.003)	−0.0826 (0.002)	1.1679 (0.042)	-	1.2455 (0.054)	1.1445 (0.027)	1.2458 (0.043)	-	1.5493 (0.053)	1.2418 (0.035)	0.864	3.019	27522
Sb	2.0392 (0.139)	0.6568 (0.031)	1.0088 (0.002)	0.1464 (0.004)	−0.1258 (0.004)	1.0179 (0.047)	-	0.9587 (0.056)	1.1891 (0.041)	-	1.0313 (0.145)	2.2039 (0.139)	1.4383 (0.050)	0.888	2.123	10351
Sw	1.1818 (0.093)	0.8231 (0.024)	1.0007 (0.001)	0.1383 (0.003)	−0.1068 (0.002)	1.003 (0.016)	1.08 (0.023)	0.948 (0.024)	1.1393 (0.017)	1.2308 (0.069)	1.0124 (0.025)	1.3077 (0.046)	1.2605 (0.024)	0.930	3.153	22863

CM = Central Mixedwood; DMW = Dry Mixedwood; LBH = Lower Boreal Highlands; LF = Lower Foothills; M = Montane; NM = Northern Mixedwood; SA = Subalpine; UF = Upper Foothills.

Table 6. Parameters estimates (reported with standard errors) and goodness-of-fit for tree diameter modeled as a function of height, crown area, basal area of the larger trees and climate, for trembling aspen and white birch, Equation (10); and for balsam fir, Equation (11), as described in Section 2.3.

Species	β_0	β_1	β_2	β_3	β_4	β_5		R^2	RMSE cm	AIC
						Climate Variable	Value			
Aw	3.3598 (0.247)	0.9965 (0.016)	-	0.1523 (0.005)	−0.09566 (0.003)	SH:M	−0.2942 (0.015)	0.899	4.259	16016
Bw	7.0926 (2.19)	0.8075 (0.021)	-	0.2275 (0.012)	−0.1363 (0.012)	AH:M	−0.4633 (0.099)	0.885	2.311	6103.9
Fb	16.3002 (2.006)	0.7491 (0.026)	0.9998 (0.002)	0.1169 (0.006)	−0.1561 (0.005)	AH:M	−0.5306 (0.041)	0.943	1.950	6297.3
Pl	7.9248 (0.615)	0.602 (0.035)	1.0145 (0.002)	0.1341 (0.003)	−0.08093 (0.002)	AH:M	−0.3323 (0.016)	0.867	2.976	27361
Sb	26.7343 (3.295)	0.6652 (0.030)	1.0092 (0.002)	0.1419 (0.004)	−0.1106 (0.004)	AH:M	−0.7204 (0.038)	0.893	2.081	10250
Sw	3.7607 (0.209)	0.8449 (0.024)	0.9993 (0.001)	0.1301 (0.003)	−0.1087 (0.002)	SH:M	−0.1383 (0.009)	0.929	3.175	22920

AH:M = annual heat:moisture index (MAT + 10)/(MAP/1000)); SH:M = summer heat:moisture index ((MWMT)/(MSP/1000)).

Table 7. Mixed model analysis (plot as the random subject): parameters estimates (reported with standard errors) of models with tree diameter modeled as a function of height, crown area, basal area of the larger trees and natural sub-regions (*i.e.*, Equations (12) and (14)), or without natural sub-regions (*i.e.*, Equations (13) and (15)), for trembling aspen and white birch, Equations (12) and (13); and for balsam fir, lodgepole pine, black spruce and white spruce, Equations (14) and (15), as described in Section 2.4.

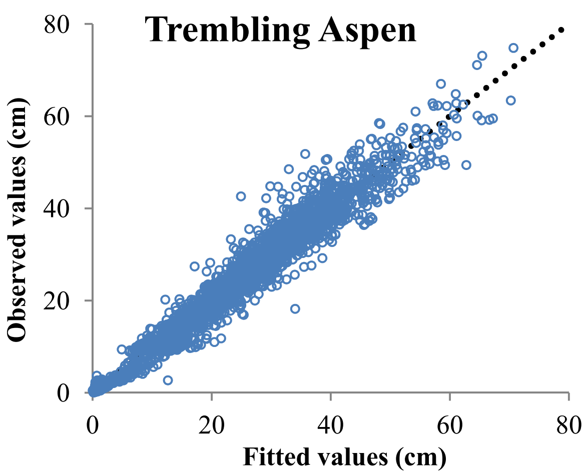
Spp.	**Eq.**	β_0	β_1	β_2	β_3	β_4	z_1	z_2	z_3	z_4	z_5	z_6	z_7	z_8	$\sigma^2_{b_0}$
							CM,DMW,NM	LF,UF	LBH	M					
Aw	(12)	2.0276 (0.105)	0.8787 (0.016)	-	0.09918 (0.004)	−0.135 (0.003)	NS	NS	−0.2191 (0.108)	NS	-	-	-	-	0.09835
Aw	(13)	2.0579 (0.104)	0.875 (0.016)	-	0.09925 (0.004)	−0.1353 (0.003)	-	-	-	-	-	-	-	-	0.1068
							CM	DMW	LBH	LF	M	NM	SA	UF	
Bw	(12)	1.7101 (0.173)	0.7842 (0.021)	-	0.2253 (0.011)	−0.2264 (0.014)	0.6924 (0.083)	1.3265 (0.270)	0.8159 (0.178)	0.7992 (0.077)	-	0.9374 (0.155)	-	1.0589 (0.206)	0.08388
Bw	(13)	2.4834 (0.176)	0.7837 (0.021)	-	0.2252 (0.011)	−0.2249 (0.014)	-	-	-	-	-	-	-	-	0.09462
Fb	(14)	2.688 (0.122)	0.7027 (0.024)	1.004 (0.002)	0.1229 (0.007)	−0.1453 (0.007)	0.3801 (0.091)	-	-	0.5904 (0.061)	-	-	1.0289 (0.158)	0.8888 (0.077)	0.05267
Fb	(15)	3.3503 (0.147)	0.6983 (0.024)	1.0045 (0.002)	0.1232 (0.007)	−0.1445 (0.007)	-	-	-	-	-	-	-	-	0.08101
Pl	(14)	1.3209 (0.126)	0.9433 (0.033)	0.987 (0.002)	0.09031 (0.002)	−0.1136 (0.002)	0.9713 (0.094)	-	0.9633 (0.162)	0.8947 (0.048)	0.736 (0.084)	-	1.0486 (0.068)	0.9126 (0.051)	0.09937
Pl	(15)	2.2224 (0.142)	0.9475 (0.033)	0.9867 (0.002)	0.09017 (0.002)	−0.1137 (0.002)	-	-	-	-	-	-	-	-	0.1026
Sb	(14)	1.6678 (0.131)	0.8271 (0.029)	0.9941 (0.002)	0.1079 (0.005)	−0.1393 (0.005)	1.0231 (0.102)	-	0.944 (0.119)	1.1825 (0.074)	-	0.9064 (0.219)	2.013 (0.284)	1.3988 (0.081)	0.09419
Sb	(15)	2.879 (0.141)	0.8342 (0.029)	0.9935 (0.002)	0.1067 (0.005)	−0.1395 (0.005)	-	-	-	-	-	-	-	-	0.1195
Sw	(14)	1.1411 (0.082)	0.8459 (0.021)	0.9987 (0.001)	0.1215 (0.004)	−0.1043 (0.002)	1.0105 (0.041)	1.1182 (0.093)	0.919 (0.079)	1.1432 (0.037)	1.1946 (0.133)	1.0319 (0.091)	1.2969 (0.110)	1.2267 (0.044)	0.04576
Sw	(15)	2.2705 (0.089)	0.8465 (0.021)	0.9986 (0.001)	0.1208 (0.004)	−0.1048 (0.002)	-	-	-	-	-	-	-	-	0.0544

Table 8. Goodness-of-fit of mixed effect models (plot as the random subject) for tree diameter modeled as a function of height, crown area, basal area of the larger trees and natural sub-regions (*i.e.*, Equations (12) and (14)), or without natural sub-regions (*i.e.*, Equations (13) and (15)). For trembling aspen and white birch, Equations (12) and (13); and for balsam fir, lodgepole pine, black spruce and white spruce, Equations (14) and (15), as described in Section 2.4. Goodness-of-fit of fixed effects models, Equations (8) and (9), are also presented for comparison purposes.

	Mixed Effect Models						**Fixed Effect Models**					
Spp.	Eq.	Par	R^2	RMSE cm	RMSE %	AIC	Equation	Par	R^2	RMSE cm	RMSE %	AIC
Aw	(12)	9	NS*	NS*	NS *	NS *	(8)	8	0.887	4.501	18.8	16328
Aw	(13)	5	0.955	2.838	11.8	14499						
Bw	(12)	11	0.927	1.849	19.9	5748.5	(8)	10	0.889	2.279	24.5	6071.6
Bw	(13)	5	0.927	1.842	19.8	5744						
Fb	(14)	10	0.956	1.713	15.6	6070.8	(9)	9	0.943	1.955	17.8	6308.4
Fb	(15)	6	0.956	1.709	15.5	6087.6						
Pl	(14)	12	0.947	1.890	8.9	23508	(9)	11	0.864	3.019	14.2	27522
Pl	(15)	6	0.947	1.889	8.9	23505						
Sb	(14)	12	0.938	1.577	11.6	9411.1	(9)	11	0.888	2.123	15.6	10351
Sb	(15)	6	0.939	1.573	11.6	9427.5						
Sw	(14)	14	0.956	2.488	12.8	21426	(9)	13	0.930	3.153	16.3	22863
Sw	(15)	6	0.956	2.484	12.8	21438						

* NS = Some parameter values are not significantly different from zero (α = 0.05).

Figure 2. Plots of predicted stem diameter against the observed stem diameter. For trembling aspen and white birch predictions are based on Equation (13); and for balsam fir, lodgepole pine, black spruce and white spruce on Equation (15), as described in Section 2.4.



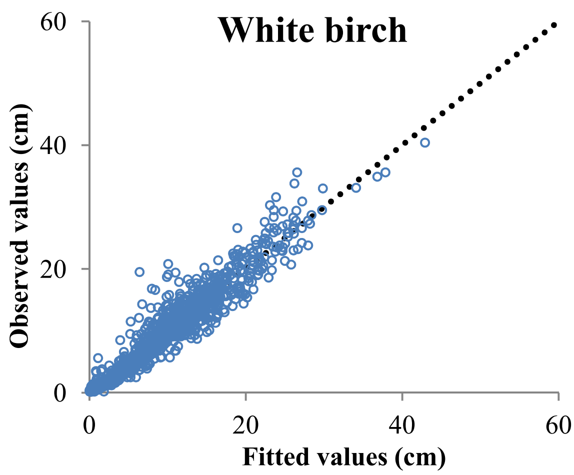
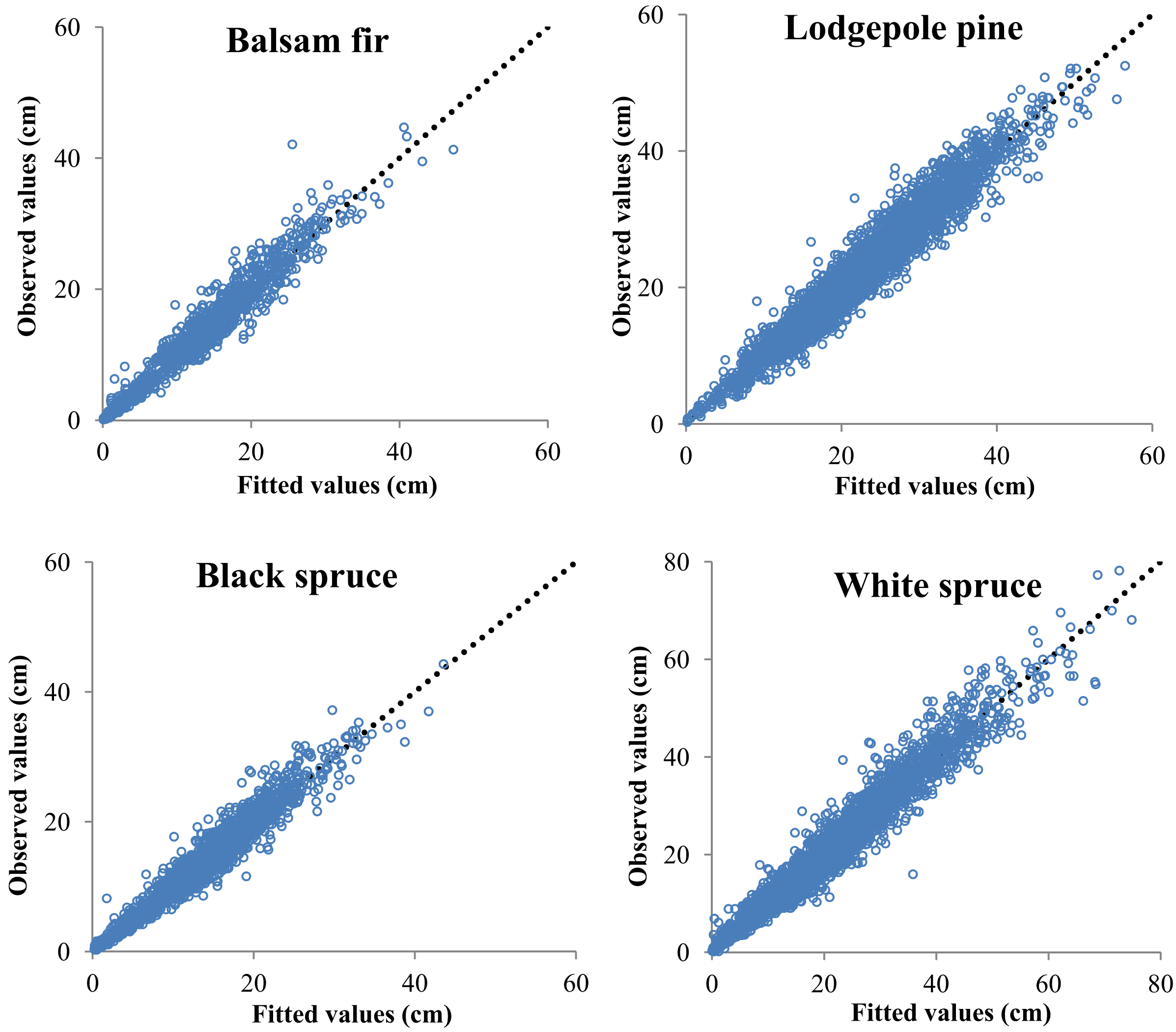


Figure 2. *Cont.*



4. Discussion

The analysis confirmed that non-linear models best represent the relationship between diameter and height [23]. The base models were significantly improved by the addition of crown area and basal area of the larger trees. These measures are linked to the tree competitive status and the availability of resources during the growing season [24], which may have a stronger influence on stem diameter than on tree height.

The fit of models was also improved by including both NSRs and climate but the inclusion of nutrient and moisture regimes was not beneficial. Other studies have shown that climatic variables can be used to improve the predictive ability of growth models [13,25] and are particularly effective for retrospective analysis including short-term updates of forest inventory [26].

The similar results obtained with climate variables and the NSRs are likely related to the strong influence of climate in defining these ecological units which are also based on landscape patterns (e.g., vegetation), soils and physiographic features [14]. Given the relatively narrow range of variability between sites in terms of moisture and nutrient regime estimates, these factors proved to have low predictive ability when added to the base models.

Grouping NSRs significantly improved model performance only for trembling aspen. This species has an extensive range and is able to grow on a variety of climates and soils [27], which may explain the possibility to group more NSRs together within the diameter model. However, trembling aspen is considered relatively sensitive to drought [28] and, considering the current warming trend [29], diameter models that account for the climatic factors should be preferred.

Accounting for nested sources of variability (e.g., plot) using mixed models further improved the diameter model fit and provided RMSE values between 1.57 and 2.84 cm, which is between 8.9 and 19.8% of average diameter. A similar study using non-linear models for conifer species in Canada have indicated RMSE values between 2.4 and 3.6 cm [30]. Recent studies have also shown that mixed-effects models are preferred for models of height and diameter [31-33].

The diameter models developed indicated that Natural Sub-Regions and climate indices (e.g., Annual Heat:Moisture index) are important factors to be considered in fixed effects diameter models, while mixed effects models are able to produce accurate diameter estimates when the variability related to plot location is taken into account. In this regard, the mixed effect models might be preferable for retrospective analysis including short-term updates of forest inventory [26], while fixed effect models with climate related variables may be more useful when investigating the relationship between diameter and height in relation to existing climate gradients across Alberta.

Several previous studies on models predicting height from diameter (e.g., [34]) indicated that the inclusion of other tree and stand parameters improves the model fit. Moreover, the asymptotic relationship between height and diameter provides for additional complexity; at the same time, it was documented that models of height and diameter are more strongly asymptotic for individual stands than for regional models [35]. While crown measures and social status may improve model fits, these attributes may also be influenced by factors such as stand age and structure, as well as site conditions. However, in our study the inclusion of site attributes (moisture and nutrient regime) did not result in a significant improvement of model prediction; comparatively the regional variation (represented in the models by the Natural Sub-Regions) provided superior predictions.

The developed models can provide accurate estimates of diameter at a regional level (*i.e.*, province of Alberta), but further studies should aim at expanding their applicability to the entire range of each tree species in order to provide generally applicable models of diameter and height. A potential issue in model application is that ground-measured tree and stand characteristics were used in model fitting. As it becomes operationally feasible to estimate these tree and stand characteristics through remote sensing techniques, it will also be possible to assess differences between ground-based and remote sensing-based estimates of the predictor variable [36]. It may be necessary to develop calibration functions to adjust any biases in the remote sensing-based estimates. In a remote sensing environment, the parameter related to the estimate of competition represented in the models by basal area of the larger trees should be recalculated by using instead crown area of competing vegetation. Crown attributes of individual trees can be derived by combining LiDAR data with aerial photographs or high resolution multispectral imagery [37].

5. Conclusions

The mixed models developed in this study provide accurate estimates of stem diameter based on height, crown area and basal area of the larger trees for several species in Alberta. Overall, the models are able to explain 95% of the variation in diameter at breast height across the six species with a root mean square error of 2.0 cm (13.4% of mean diameter). Fixed effect models with the inclusion of Natural Sub-Region (NSR) information are able to explain 90% of the variation in diameter at breast height across the six species with a root mean square error equal to 2.8 cm (17.9% of mean diameter). Selected climate variables provided similar results to models with NSR information. These models are a step forward in allowing the prediction of stem diameter at regional level using measurements of height and crown area provided by remote sensing.

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Conflict of Interest

The authors declare no conflict of interest.

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