Predicting the Diameter of the Largest Breast-Height Region Branch of Douglas-Fir Trees in Thinned and Fertilized Plantations

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Abstract

Diameter of the largest limb in the breast height region (DLLBH) of trees is a good predictor of largest limb average diameter, a log knot index used in product recovery studies to predict product grade mix and value. DLLBH was measured on 2,252 Douglas-fir (*Pseudostuga menziesii* (Mirb.) Franco) trees from nine sites each with three plot pairs established at age 6 to 13 years. One of each pair was thinned, and the other was thinned and fertilized with 224 kg ha^{-1} N as urea at establishment and every four years thereafter. DLLBH was measured at age 21 to 31 years when BH branches were dead. Fractional polynomials were used to develop models to predict DLLBH. One model ($r^2_{adj} = 0.69$, root mean square error [RMSE] = 4.86) used only tree variables: diameter at breast height (DBH), total height, height to crown base, taper, and tree social position in the stand. A model that included treatment (if fertilized or not), stand density, and site index was a significant improvement ($r^2_{adj} = 0.72$, RMSE = 4.62). The tree-variables-only model and the combined tree and stand variables model can be used with individual tree growth models to estimate the distribution of tree DLLBH in a stand for use with process capability analysis to assess conformance with external tree quality specifications. A model using variables measurable with light detection and ranging and knowledge of site index and treatment history was also developed ($r^2_{adj} =$ 0.56, RMSE = 5.78). This model suggests that there is an opportunity to use remote sensing to obtain and map (using a geographic information system) preharvest distributions of tree DLLBH in stands across a landscape for harvest scheduling and silvicultural planning.

Management of Douglas-fir (*Pseudostuga menziesii* (Mirb.) Franco) has shifted to intensively managed plantations (Talbert and Marshall 2005), which led to questions concerning how wood quality and product value would be affected. Consequently, several reviews and mill studies were conducted to address the wood quality–product value issue, and all agree that the number and size of branches that become knots in products is a critical factor affecting quality and value (Megraw 1986, Kellogg 1989, Fahey et al. 1991, Jozsa and Middleton 1994, Aubrey et al. 1998, Zhang et al. 2002). Mill studies have found that largest limb average diameter (LLAD) or branch index, obtained by averaging the diameter of the largest knot in each of the four lengthwise faces of a log, is an excellent predictor of product grade mix and value (Fahey et al. 1991, Aubrey et al. 1998). More recent studies have found that the LLAD of the first (butt) log in Douglas-fir trees can be predicted from the diameter of the largest limb in the breast height region (DLLBH; Briggs et al. 2005, 2007). Since DLLBH is a good predictor of log quality, it can be used to assess and monitor the influence of silvicultural practices (Briggs et al. 2005). An advantage of DLLBH is that it is a simple, nondestructive, preharvest measurement that can be incorporated into timber cruising with little impact on field crew time or cost. Although DLLBH is simple to measure, visits to field plots may be too expensive and too limited over time and space for planning, monitoring, and other purposes. Consequently, it would be desirable to develop models to improve understanding of how tree, stand, and silvicultural treatment variables affect DLLBH. Combining DLLBH, DLLBH–

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LLAD, and product recovery models with growth and yield models would permit prediction of the effects of silvicultural regimes along the tree-to-product value chain. Furthermore, with the development of light detection and ranging (LIDAR) remote sensing technology for measuring height, crown, and density attributes of forest stands (Popescu and Zhao 2008, Erdody and Moskal 2010), it may be possible to develop models to estimate DLLBH based on attributes measured by LIDAR. This would permit mapping DLLBH, or log quality, as an attribute in geographic information systems to assist in silvicultural and harvest planning.

Many studies have investigated the effects of tree, stand, and treatment variables on branch growth and longevity, and good reviews can be found elsewhere (Kershaw et al. 1990, Kozlowski and Pallardy 1997, Makinen and Colin 1998, Makinen 1999a, Protz et al. 2000, Briggs et al. 2008). Most studies have focused on live branches and have generally found that factors such as thinning, fertilization, and higher site quality that favor faster stem diameter growth also favor faster branch diameter growth. This leads to larger knot diameters observed on log surfaces by log graders and larger knots that degrade product value. After branch death, the stem grows over the dead branch and diameter observed on the stem or log surface gradually decreases due to branch taper, shrinkage as wood in the dead branch dries, and loss of bark. Consequently, many of the factors that stimulated faster growth leading to larger diameter live branches have the opposite effect on the diameter of dead branches by promoting faster stem growth to encase them.

We previously developed models to predict the mean, stand-level DLLBH at the stem surface of trees from thinned, fertilized Douglas-fir stands using mean tree, treatment, and stand variables (Briggs et al. 2008). Stand mean DLLBH increased with higher site index, increased with larger mean tree diameter at breast height (DBH), decreased with higher mean tree total height (HT), and decreased with higher mean height to the crown base (HCB). A model restricted to variables that could be measured with LIDAR, current stems per hectare count (CSTEMS), and HCB, combined with knowledge of site index and treatment history, was also developed. While stand mean DLLBH models are useful for integration with stand-level growth models and decision support systems, counterpart models to make predictions at the individual tree level would be useful for integration with individual tree growth models. Therefore, the objectives of this analysis were as follows.

1. To model DLLBH of individual trees using only tree-level variables. With this objective we propose the hypothesis that dimensional and social status variables of individual trees reflect the effects of stand density, treatments, site index, and other growing environment variables. Several studies have indicated that only individual tree variables are needed to model branch diameter (Colin and Houllier 1991, 1992; Doruska and Burkhart 1994; Roeh and Maguire 1997; Maguire et al. 1991, 1994, 1999; Vestol et al. 1999). A model of this form would be useful to managers when they have tree data but lack information on stand, treatment, and growing environment variables.
2. To assess the improvement, if any, when stand density, treatments, site index, and other growing environment variables are included. With this objective we propose the hypothesis that including stand density, treatment, site index, and other growing environment variables will improve upon models using only tree variables. Some studies have found that models that combine individual tree variables with stand and treatment variables improved upon models with only tree variables (Grotta et al. 2004, Garber and Maguire 2005, Briggs et al. 2008). If a model of this form improves upon the Objective 1 model, managers that have both tree data and knowledge of stand, treatment, and growing environment variables could develop more refined predictions of DLLBH.
3. To develop a model for predicting tree-level DLLBH using only variables that can be measured by LIDAR or would be known from stand records such as site index and treatment history. If a model of this form can be developed, managers could use LIDAR to estimate DLLBH and combine it with a geographic information system to map information about tree quality in stands over a landscape.

Materials and Methods

Experimental design and measurement of DLLBH

Spacing and fertilization trials were established in nine Douglas-fir plantations in western Oregon and Washington at age 6 to 13 years (Table 1). At each installation, six plots were created, two at the original stems per hectare on the site, two that were thinned to 50 percent of the original stems per hectare, and two that were thinned to 25 percent of the original stems per hectare. Each pair of plots was assigned a future thinning regime based on relative density (Curtis 1982), and one member of the pair received 224 kg ha^{-1} (200 lb/acre) N as urea at plot establishment and every 4 years thereafter. Further details of conditions on each site and the thinning regimes are in Briggs et al. (2008). The installations were planted between 1974 and 1984, with the site preparation, planting stock, and vegetation control practices each landowner deemed best for the site. Consequently there is wide variation in the regeneration practices among the sites. The thinning at establishment was systematic, so the size of trees in the residual stand was not significantly changed. When plots were established and initially treated, the base of the live crown was below BH so BH region branches were alive and capable of responding to treatments. The BH region, chosen for measurement convenience, contains the first whorl above BH and half the distance to the next higher and next lower whorl. Between 2002 and 2004, DLLBH was measured on approximately 40 trees on each plot (2,257 in total). By this time, stand age was 18 to 29 years since planting, 21 to 31 years from seed, and virtually all BH branches were dead. The nine, six-plot installations form a randomized complete block design with installations as the blocking factor accounting for physiographic factors; on each installation is a two-way factorial effect of the randomly assigned thinning and fertilization factors.

Analysis procedure

Table 2 presents definitions and statistics of variables used in the analysis. Since installations were measured

Table 1.—Characteristics of the nine Type I installations within the density management-fertilization experiment.

Characteristic[a]	Installation no.								
	704	705	708	713	718	722	725	726	736
County	Cowlitz	King	Lewis	Skagit	Linn	Marion	Jefferson	Lincoln	King
State	WA	WA	WA	WA	OR	OR	WA	OR	WA
Latitude	44°12′47″	47°10′36″	46°27′30″	48°30′4″	44°39′11″	44°52′27″	47°53′49″	44°41′30″	47°35′39″
Longitude	122°50′49″	121°43′4″	122°4′8″	121°37′36″	122°40′16″	122°33′58″	122°46′25″	123°56′34″	121°43′31″
Elevation (m)	183	823	274	242	335	671	168	91	183
Slope (%)	20	30	5	5	10	10	0	10	40
Aspect[b]	270	180	999	180	888	270	999	225	270
Site index 50, (m)[c]	37	27	38	37	39	37	37	41	37
Site index 30, (m)[d]	25	23	28	27	28	22	27	28	28
Planting date	Jan 1974	Jan 1976	Jan 1981	Feb 1978	Jan 1982	Feb 1977	Dec 1980	Jan 1984	Mar 1984
Stock type	2-0,2-1,1-1	1-1	1-1	Unk	2-1,2-0	2-0	1-0	1-1	2-0
No. of trees ha^{-1}, install. estab.[e]	1,420	1,729	1,062	1,329	988	1,359	1,112	894	1,112
Year install. estab.	1987	1987	1988	1988	1989	1989	1990	1990	1992
Age, plant to estab. install. (y)	13	11	7	10	7	12	10	6	8
DLLBH meas. date	2003	2003	2004	2004	2001	2001	2002	2002	2004
Age, plant to DLLBH meas. (y)	29	27	23	26	19	24	22	18	20

[a] install. = installation; estab. = established; meas. = measured.
[b] Degrees azimuth: 888 = variable aspect; 999 = flat, no aspect.
[c] Site index 50, based on breast height age, is from King (1966).
[d] Site index 30, based on age from seed, is from Flewelling et al. (2001) and is the mean for all plots on the installation calculated 8 years after establishment.
[e] Mean of the four ISPA plots on each installation.

Table 2.—Variable definitions and statistics.

Variable	Description	Mean (SD)	Min.	Max.
Dependent variable				
DLLBH	Diameter of the largest limb in the BH region of a tree (mm)	25.3 (9.22)	5.1	63.5
Independent treatment effect variables				
ISPA1, ISPA2, ISPA4	Binary (0,1) variables. Code = 1 if plot has 100% (ISPA1), 50% (ISPA2), or 25% (ISPA4) of trees per unit area at plot establishment; code = 0 otherwise			
FE	Binary (0,1) variable. Code = 0 if plot was not fertilized; code = 1 if fertilized with 224 kg/ha (200 lb/acre) N as urea at establishment and every 4 y since			
Independent plot variables, $n = 54$				
ISTEMS	Avg trees per hectare present at establishment on the entire installation before spacing to the ISPA densities	1,297 (421.8)	697	2,550
IRD	Curtis' relative density (1982) at establishment before spacing to the ISPA densities; plot basal area, m^2/QMD, $cm^{1/2}$	2.3 (1.3)	0.7	5.9
SI_{30}	Flewelling et al. (2001) 30-y site index calculated from plot data closest to age 20 y (m)	26.5 (2.35)	21.6	29.9
PSTEMS	Trees per hectare present after establishment respacing on each plot	685 (455.5)	188	2,096
CSTEMS	Trees per hectare present at the time of DLLBH measurement	504 (2,082)	163	1,077
PRD	Curtis' relative density (1982) at establishment after respacing each plot; plot basal area, m^2/QMD, $cm^{1/2}$	1.2 (1.0)	0.2	4.7
HT40	Avg height of the 40 largest trees by DBH (m)	20.41 (2.77)	15.94	26.79
QMD	Quadratic mean DBH (cm)	27.5 (4.66)	19	39
Independent tree variables, $n = 2,252$				
Y_Until_CR	Elapsed years from spacing at establishment until the crown receded above BH (used first measurement cycle when crown height > BH)	8.3 (3.86)	0	16
Y_Since_CR	Elapsed years since the crown receded above BH until the latest BH branch measurement	5.9 (4.28)	0	17
DBH	Diameter at breast height (cm)	26.8 (7.18)	7	52
HT	Total height (m)	18.8 (3.20)	8	30
HCB	Height to crown base (m) measured as lowest point with a live branch in three of four quadrants	7.5 (3.32)	0	17
HT/DBH	Ratio of total height to DBH (cm/cm)	74.2 (19.1)	22	168
CL	Crown length = HT − HCB (m)	11.3 (2.96)	1	23
CR	Crown ratio = 1 − HCB/HT	60.5 (15.11)	8	100
HT/HT40	Ratio of total height of a subject tree to the mean total height of the 40 largest trees by DBH; an indicator of social position of the subject tree in the stand	0.92 (0.112)	0.40	1.125

every 4 years, the year when BH branches died was estimated as the first remeasurement year when the crown base, defined as the lowest whorl in which live branches are in three of the four quadrants of the crown, exceeded BH. The 4-year interval, crown base definition, and location of the first whorl above BH combine to cause a discrepancy between the actual year of death of the largest diameter branch in the BH region and our estimate. We did not attempt to interpolate the year of largest BH branch death within the 4-year measurement interval.

Our data possess hierarchical structure, that is, trees are nested within plots, which are nested within blocks. Under some circumstances, building models to account for this structure would be appropriate. However, we deliberately chose not to analyze this way because we want results to be generally applicable to any size and shape of plot and any configuration of blocks. This is commonly done for similar reasons when building individual-tree-growth models such as the California conifer timber output simulator (CACTOS; Wensel et al. 1987, Wensel and Biging 1988), the forest vegetation simulator (Wykoff 1990, Dixon 2002), and the Oregon growth analysis and projection model (ORGANON; Hann 2009), which again are where we see our models ultimately being used. We realize that this essentially pools between plot and between block variance into the error term (mean squared error). In some sense, this can be viewed as the classic tradeoff between choosing a randomized complete block design over a completely randomized design, in which case degrees of freedom are traded between the blocking factor and the error term. If between block variance is pooled into the error term, the error term is inflated and less power may be available for detecting treatment differences, depending on how much the error term degrees of freedom increase in compensation. We are confident that any statistical discoveries made using least squares regression analysis will reflect real, not spurious, findings.

Preliminary data plots and analyses revealed many nonlinear relationships. In such cases, polynomial regression, where powers are positive integers, is frequently used. However, polynomial regression has weaknesses including lack of flexibility of low-order quadratic and cubic polynomials, production of waves and ''tail effects'' of high-order polynomials, and inability to model relationships where asymptotic behavior is expected (Royston and Altman 1994). Box and Tidwell (1962) developed an iterative method of power transformation of the independent variables, but reliable estimation of powers is difficult for models with more than one variable (Royston and Altman 1994). To overcome the limitations of polynomials, Royston and Altman (1994) developed fractional polynomials (FP) for the case of a single variable and suggested a procedure for the case of multiple variables (MFP). The FP of degree M for variable X is $\mathrm{FP}(M) = \beta_0 + \Sigma_{m=1}^{M} \beta_m X^{p_m}$, where p_m is a member of the set S. Royston and Altman (1994) proposed $S = \{-2, -1, -1/2, 0, 1/2, 1, 2, 3\}$, where $p = 0$ is either ln(X) or log(X). Set S contains eight possible $\mathrm{FP}(1) = \beta_0 + \beta_1 X^{p1}$ models including no transformation when $p = 1$, the straight line, and 7 transformation options including the reciprocal, logarithmic, square root, square, and cube. No subsequent changes in S have been proposed as experience and many studies have found that this set works well. Extension to two term $\mathrm{FP}(2) = \beta_0 + \beta_1 X^{p1} + \beta_2 X^{p2}$ models with powers ($p1$, $p2$) from set S produces 36 possible transformations including repeated powers, $\mathrm{FP}(2) = \beta_0 + \beta_1 X^{p1} + \beta_2 X^{p1} \ln(X)$ when $p1 = p2$ (Royston and Altman 1994).

MFP, which can include binary, categorical, and other continuous variables that do not need transformation, was refined by Sauerbrei and Royston (1999). MFP combines backward elimination with an adaptive algorithm that selects the best FP transformation for each continuous variable from a specified nominal α value. At each step of the backfitting algorithm, MFP constructs an FP transformation of each continuous variable while fixing the current functional form of the other covariates and terminates when no more covariate is excluded and the functional forms of the continuous variables cease changing. Model selection uses the following closed test procedure (Sauerbrei et al. 2006). First, perform a 4 df test at the α level of the best fitting FP(2) against the null model. If the test is not significant, drop x and stop; otherwise, continue to Step 2. Second, perform a 3 df test at the α level of the best fitting FP(2) against the straight line FP(1). If the test is not significant, stop, because the final model is the straight line; otherwise, continue to Step 3. Third, perform a 2 df test at the α level of the best fitting FP(2) against the best fitting nonlinear FP(1). If the test is significant, the final model is the FP(2), otherwise the best model is the FP(1).

Models to predict DLLBH from variables in Table 2 were constructed in Stata using program MFP and Fracpoly (STATA 2003, Sauerbrei et al. 2006). Selecting suitable final models to satisfy each of our three objectives involved comparing many candidates. Only models in which all parameter coefficients were statistically significant ($P \leq 0.05$) were considered to be candidates. One model was considered better than another when it had a lower standard error of the estimate, lower Aikake's information criterion (AIC), and higher adjusted r-squared. Variance inflation factors were also examined to guard against the inclusion of variables that were too highly correlated with other variables already in the model. Finally, a likelihood ratio test was performed to determine whether the final model that combined tree, stand, and treatment variables was significantly different from the best model with only tree variables.

Results

Using only the tree variables in Table 2, the best model for predicting DLLBH is shown in Table 3, Model A ($r^2_{adj} = 0.69$, root mean square error [RMSE] = 4.86, AIC = 6.0). This tree-variables-only model is consistent with others who found that only individual tree variables were needed to model branch diameter (Colin and Houllier 1991, 1992; Doruska and Burkhart 1994; Roeh and Maguire 1997; Maguire et al. 1991, 1994, 1999; Vestol et al. 1999). DLLBH increases linearly as DBH increases and as the ratio of the total height of the subject tree to the mean height of the 40 largest DBH trees (HT/HT40) increases, which can be interpreted as a measure of social position of the subject tree in the stand. DLLBH decreases linearly with increasing HCB an indicator of time since death of BH branches. DLLBH increases with the square of DBH/HT, an indicator of tree taper. DLLBH decreases with the square of HT; an indicator of more shading on, and lower social position of, the BH branch within the tree. Plots of residuals appeared to be centered on zero with an increasing variance pattern, so we used weighted least squares with DBH/HT as a weight to

Table 3.—Models to predict DLLBH (mm) of individual trees from (A) tree variables, (B) tree, stand, and treatment variables, and (C) variables measurable with LIDAR and known from management records.

Variable	Estimated value	SE
Model A. DLLBH from tree variables RMSE = 4.86, r^2_{adj} = 0.69, AIC = 6.0		
Intercept	−1.94	1.01
DBH	0.350	0.0734
HT^2	−0.0224	0.00264
$(DBH/HT)^2$	3.91	0.472
HCB	−0.138	0.0511
HT/HT40	20.1	1.34
Model B. DLLBH from tree, stand, and treatment variables RMSE = 4.62, r^2_{adj} = 0.72, AIC = 5.9		
Intercept	−15.2	1.44
DBH	0.299	0.0707
HT^2	−0.0163	0.00272
$(DBH/HT)^2$	3.57	0.456
HT/HT40	16.5	1.39
HCB	−0.226	0.0520
FE	0.758	0.197
SI	0.667	0.0486
PRD^3	0.0438	0.00704
$PSTEMS^2$	−0.00000117	0.000000160
Model C. DLLBH from variables measured by LIDAR and known from management records RMSE = 5.78, r^2_{adj} = 0.56, AIC = 6.4		
Intercept	8.37	1.19
HT	−0.299	0.0776
$HCB^{1/2}$	−3.79	0.350
HT/HT40	29.1	1.68
CSTEMS	−0.0102	0.000720
SI	0.000471	0.00003
FE	1.45	0.248

[a] DBH = diameter at breast height (cm); HT = total height (m); HCB = height to crown base; HT40 = mean height of 40 largest DBH trees; FE = fertilized (1) or not fertilized (0); SI = Flewelling et al. (2001) site index (m); PRD = Curtis (1982) relative density immediately following thinning at plot establishment; PSTEMS = trees per hectare immediately following thinning at plot establishment; CSTEMS = trees per hectare at time of DLLBH measurement.

resolve heteroskedasticity. However, plots of residuals on stand and treatment variables in Table 2 revealed potential opportunities for improvement.

When stand and treatment variables in Table 2 were considered, the best model for predicting DLLBH, Model B in Table 3, includes the same tree variables as Model A. However, Model B also shows that DLLBH increased about 0.8 mm if the tree was fertilized and increased by about 0.7 mm with increasing site index. DLLBH increases with the cube of plot relative density (PRD) immediately after the thinning at establishment and decreases with the square of the number of stems per hectare present immediately after the thinning at establishment. By including the treatment and stand variables, r^2_{adj} increased to 0.72, RMSE decreased to 4.62, and AIC decreased to 5.9. A likelihood ratio test to assess the null hypothesis that Model B (Table 3) was not different from Model A was rejected ($P < 0.0001$). Therefore, we conclude the added stand and treatment terms do explain a significant proportion of the variation left after accounting for tree variables. We also examined the variance inflation factors for the added variables as well as the individual tree variables. Though some of them were high (>10), we kept all the variables in the model because of their real biological interpretability as well as their extremely small *P* values. The improvement by including stand and treatment variables is consistent with others who show that branch diameter predictions are improved when tree, stand, and treatment variables are combined (Grotta et al. 2004, Garber and Maguire 2005, Briggs et al. 2008). Partial regression plots, which present the marginal role of each independent variable given that the others are already in the model, are presented in Figure 1. They reveal the nature of the relationship of each independent variable with DLLBH.

To find a model to predict DLLBH using only variables that can be measured by LIDAR or would be known from stand records, we restricted the variables to include only the various height measurements, CSTEMS count, site index, and whether the stand had been fertilized. Model C in Table 3 (r^2_{adj} = 0.56, RMSE = 5.78, AIC = 6.4) incorporates linear terms of total height, CSTEMS, tree social status (HT/HT40) and fertilization and nonlinear terms of HCB and site index. While HCB measured from the ground to the first whorl with live branches in three quadrants is likely to differ from height to the crown base measured with LIDAR, several studies have found that LIDAR and ground based measurements of HCB are highly correlated (e.g., Popescu and Zhao 2008, Erdody and Moskal 2010).

Discussion

In Models A and B (Table 3), DLLBH at the stem surface is larger if the DBH of the tree is larger. This would be expected from allometry, and the positive effect of DBH on branch diameter has been found by others (Maguire et al. 1991, 1999; Doruska and Burkhart 1994; Pape 1999; Vestol et al. 1999; Grotta et al. 2004; Briggs et al. 2008). The positive DBH effect can be interpreted to mean that, after thinning at age 8 to 13 years when BH branches were alive, larger DBH trees grew larger BH branches, which set the stage for measurement of larger DLLBH of the dead branches at age 21 to 31 years. DLLBH of a tree is larger if taper or ''stoutness'' of a tree is greater. For a given height, a larger DBH (i.e., higher DBH/HT ratio implies faster growth) and faster growing trees would be expected to produce a larger DLLBH. A similar effect was found by Makinen (1999b). DLLBH of a tree is larger if the tree's social status in the stand, indicated by the ratio HT/HT40, is greater. It would be expected that more dominant trees in a stand would be faster growing and produce larger DLLBH. This is in agreement with Garber and Maguire (2005), who found larger diameter branches in trees of higher social status.

In Models A, B, and C (Table 3), DLLBH is smaller in trees with greater total height. Greater total height is indicative of greater distance from the top of the tree to the BH region, indicating more shading of the BH region. It is likely that the largest BH branch in relatively tall trees became slow growing and died relatively early and would be relatively small. This would allow more time for the stem to grow over the small tapered branch, reducing the diameter measured at the stem surface. DLLBH is smaller if the tree has a greater HCB, indicating more distance between the BH region and the live crown base, implying more time since branch death and thus more time for the

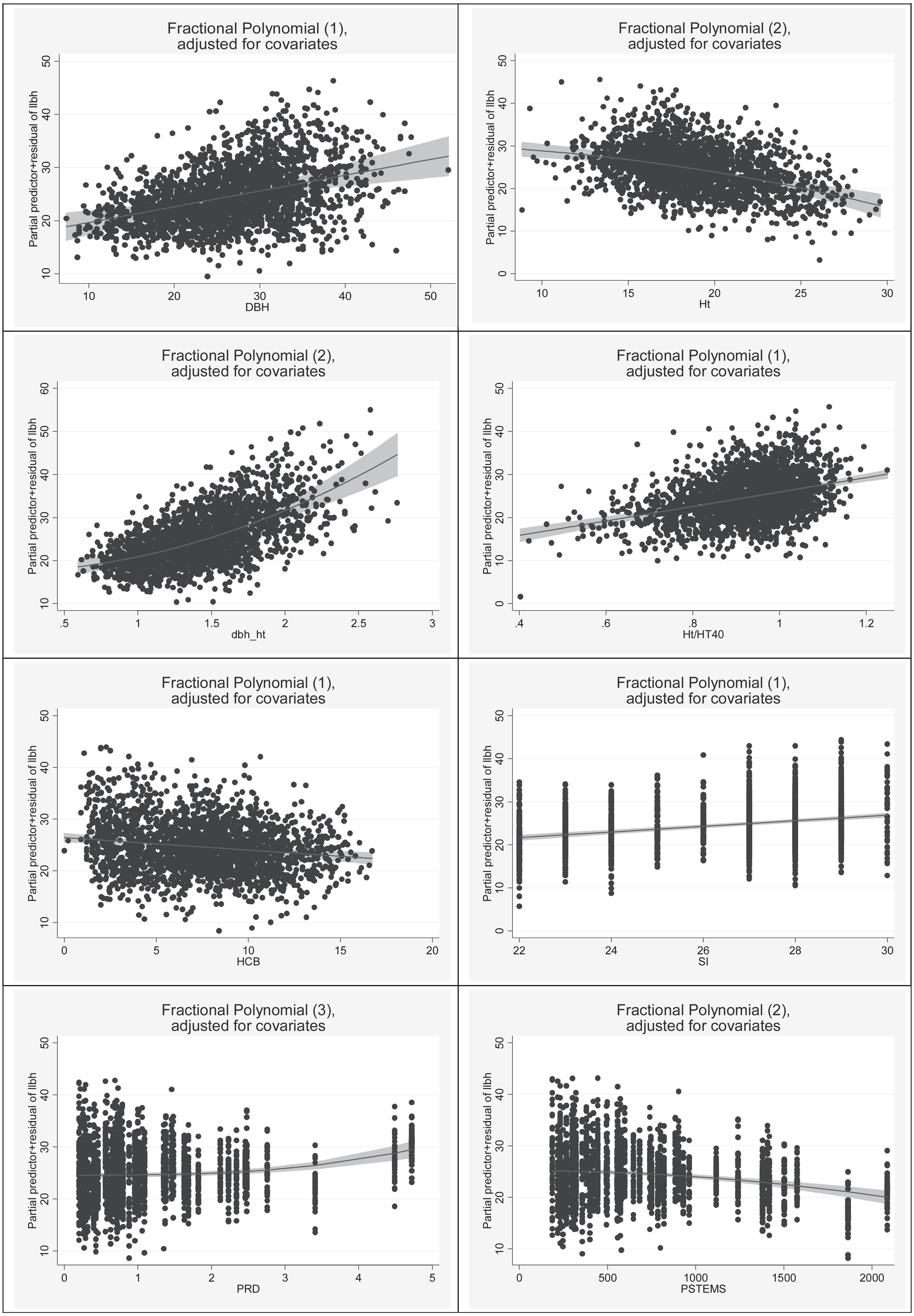

Figure 1.—Partial regression plots for the Table 3 Model B to predict DLLBH.

tree to grow over the progressively smaller dead branch. This is consistent with Briggs et al. (2008).

In Models B and C, DLLBH of a tree is greater if the tree grew on higher quality land (SI). Many studies reported larger diameter branches on trees growing on more productive sites (Tombleson et al. 1990, Usvaara 1990, Maguire et al. 1991, Moberg 1999, Briggs et al. 2008), but others have found no effect of site quality (Maguire et al. 1999). Possible explanations for the lack of agreement may lie in the range of site conditions considered by the different studies as well as sample design. For example, Maguire et al. (1999) sampled two trees from 40 plots (96 total), Maguire et al. (1991) sampled 338 trees, and we sampled nine sites each with six plots and about 40 trees per plot. Statistical power associated with the various studies may underlie differences in their ability to detect significance of some variables.

In Models B and C, DLLBH of a tree was also greater if the tree grew in a fertilized stand, consistent with others (Madgwick et al. 1986, West 1998, Kimberley et al. 2003, Albaugh et al. 2006, Briggs et al. 2008). When plots and treatments were established in our study, all trees had the base of the live crown below BH, so branches in the BH region were alive and able to respond to the treatments; branches will grow larger with more productive growing conditions, but higher sites and fertilization may either increase or decrease longevity depending on stand density. Although branches were dead when DLLBH was measured in this study, higher site index and fertilization likely produced bigger BH branches before they died, setting the stage for measurement of larger DLLBH on dead branches years later.

In Model B, DLLBH is larger if the tree was in a plot with a higher PRD immediately following the thinning at plot establishment at age 6 to 13 years. Relative density, basal area relative to the quadratic mean DBH of trees in a stand, is a measure of site use commonly used as a thinning guide (Curtis 1982). Since the thinning at establishment systematically removed 50 or 75 percent of the trees, a high relative density of the residual stand reflects a high relative density and high level of site use by the stand prior to treatment. Trees in young Douglas-fir plantations have greater height and greater DBH in dense as compared with widely spaced plantings, a phenomenon referred to as the ‘‘crossover effect,’’ which lasts until about age 13 to 14 years (Scott et al. 1998, Turnblom and Pittman 2001). When our study plots were established at age 6 to 13 years, the more densely planted installations had larger trees and higher relative density due to this effect (Turnblom and Pittman 2001). Since trees were larger on the higher relative density installations, they would likely have larger DLLBH when the treatments were imposed. Measurement of PRD immediately after thinning likely captures the pretreatment differences due to the crossover effect. Also, since BH branches were alive at plot establishment, PRD immediately following treatment may be an indicator of subsequent differences in live branch growth rate and longevity, a topic for future research. This effect was also found in our previous study of plot mean DLLBH (Briggs et al. 2008). In contrast, Maguire et al. (1991, 1999) found a negative effect and no effect, respectively, of relative density on branch diameter. The difference may be reconciled by the previously noted sampling differences and noting that we used initial condition relative density immediately after the establishment thinning to predict later diameter of dead branches, whereas Maguire et al. (1991, 1999) used current relative density as a measure of current competition to predict diameter of live branches. More comprehensive studies are needed to fully understand the effects of how treatments and stand density measures affect branch diameters Although fertilization is explicit in Models B and C, the effects of thinning were taken into account by tree and stand variables that measure the development of larger diameter BH branches between the time of establishment and branch death; these variables determined its diameter at the time of death, after which the tree grows over the dead tapered portion leaving a smaller diameter to be measured at the stem surface.

In Models B and C, DLLBH is smaller if the tree grew in a stand with more stems per hectare (just after the thinning at plot establishment [PSTEMS] and at the time of DLLBH measurement [CTEMS]). Higher stems per hectare increased shading on BH branches, which would be smaller as shading slowed their growth and accelerated their death. This would set the stage for measurement of relatively smaller DLLBH in higher density stands after branch death. Other researchers have found a negative effect of high stand density on branch diameter (Grah 1961, Ballard and Long 1988, Johansson 1992, Scotti 1999, Vestol et al. 1999, Baldwin et al. 2000, Zhang et al. 2002, Briggs et al. 2008). Althouth PSTEMS in Model B was a better predictor than CSTEMS in Model C, PSTEMS was not allowed in Model C because LIDAR would be able to count only the CSTEMS, not the count when precommercial thinning occurred in the past.

Management Implications

The three individual tree DLLBH models will be useful to managers with the choice depending on information that is available. If a manager only has data on individual trees, the tree-variables-only model (Model A) can give good DLLBH predictions, but the predictions would be improved if the manager also has knowledge of the stand density, treatment, and site index in the combined variable model (Model B). If remote sensing with LIDAR is available, the LIDAR model (Model C) indicates that there is a potential to predict DLLBH with remote sensing. For this potential to be realized, research is needed where both LIDAR coverage and DLLBH measurements on field plots are collected allowing development of models to predict DLLBH from LIDAR metrics. A LIDAR model creates the opportunity to map DLLBH of trees in stands over a landscape. This could be integrated into a geographic information system to provide managers with information on distribution of volume available within DLLBH strata of each stand as well as the spatial location of volume in the chosen strata over a landscape. This knowledge of the amount of volume of each stratum is present and where it is located would be useful for planning silvicultural treatments and harvests to better match markets.

The DLLBH models could be combined with equations that relate the DLLBH of a tree to the LLAD of the first log within it (Briggs et al. 2005, 2007) and with product recovery and value studies (Fahey et al. 1991, Aubrey et al. 1998) to create linkage along the value chain. Specific applications depend on the perspective of the decision maker, tree grower, or tree buyer and on the particular value(s) of DLLBH that is chosen to provide the desired level(s) of stratification. For example, a mill could start with product recovery grade mix equations or graphs (e.g., Fahey et al. 1991) to select desired log quality (LLAD) strata needed to meet a desired mix of product grades for its markets. The selected log LLAD strata can be readily converted to tree DLLBH through an LLAD/DLLBH equation (e.g., Briggs et al. 2005, 2007). The resulting DLLBH specifications can be overlaid on the DLLBH distribution of trees in a stand to determine the portions of the stand that are within each stratum. This allows the buyer to have a preharvest estimate of the conformance of stands to its product mix needs. This is an application of process capability analysis (Briggs et al. 2005), a flexible tool for assessing how market change may alter raw material quality specifications. The process capability analysis approach corresponds to the ''proprietary grades'' that many mills use to sort raw material according to changing markets. Forest managers can use Models A and B with an individual tree growth model and observe the effect of alternative management regimes on the proportions of the simulated stand that fall within the desired DLLBH strata. In the case of a variable such as PRD, one can use model simulations to observe how practices that produce higher or lower PRD alter proportions of a stand falling into the DLLBH strata.

The individual tree DLLBH models in this article are counterparts to stand-level models for mean DLLBH reported previously; the choice of which ones to use depends on information available and objectives of the user. Those using a stand-level growth model and decision support tools would likely use the stand-level DLLBH models (Briggs et al. 2008), while those using tree-level growth models, process capability analysis, and other tree-level decision tools would likely use the models from this study.

There are limitations to using the models developed in this study. First, they predict DLLBH of dead branches only; a result of the age and crown recession of the trees when the DLLBH measurements were taken. Second, the models should not be used to extrapolate beyond the domain of the independent variables indicated in Table 1. Third, DLLBH was only measured one time on each branch; repeated measurements, starting before crown recession above BH, would permit the development of more robust, dynamic models of the development of DLLBH. Collection of repeated measurements to develop dynamic models of branch diameter is under way in other Douglas-fir spacing trials.

Conclusion

This study modeled the diameter of largest branch in the BH region, DLLBH, of individual Douglas-fir trees from thinned and fertilized plots several years after the BH branches had died. One model uses only tree variables—DBH, height, HCB, and social position—to predict DLLBH. However, a model that also includes stand density, site index, and knowledge of whether the stand was fertilized was found to be a statistically significant improvement. A model restricted to variables that would be known from management records and measured by LIDAR remote sensing provides the opportunity to use LIDAR to map DLLBH as a wood quality indicator at the landscape level. Although the models were developed for the diameter of the largest branch in the BH region of individual trees, we believe the approach could be extended to model the diameter of the largest branch in other regions, keeping in mind that the present models are only applicable to branches below the base of the live crown.

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