Effect of precommercial thinning followed by a fertilization regime on branch diameter in coastal United States Douglas-fir plantations

David G. Briggs, Rapeepan Kantavichai, and Eric C. Turnblom

Abstract: The effect of precommercial thinning in 6- to 13-year-old Douglas-fir (*Pseudostuga menziesii* (Mirb.) Franco var. *menziesii*) plantations with and without fertilization with 224 kg·ha^{-1} nitrogen (N) as urea on the mean diameter of the largest limb at breast height (DLLBH) was modeled. DLLBH is a simple, nondestructive field measurement related to log knot indices used to measure log quality in product recovery studies. Model [1] succeeded in predicting mean DLLBH (RMSE = 2.80 and r_{adj}^2 = 0.84) using only site, initial stocking, and treatment variables. Model [2], which used only mean tree variables, improved on model [1] and was simpler. However, model [3], which used a combination of both groups of variables, produced the best model. Model [4] successfully predicted mean DLLBH using variables that can be measured with light detection and ranging (LIDAR), a high-resolution remote sensing technology. Since the age when the live crown receded above breast height is an important variable in some of the models, model [5] was developed to predict when crown recession above breast height occurs. This study found that mean DLLBH of Douglas-fir plantations can be estimated using variables obtained from stand-level growth models or remote sensing, providing a quality indicator that can be easily measured and verified in the field.

Résumé : Nous avons modélisé l'effet de l'éclaircie précommerciale dans des plantations de douglas de Menzies (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*) âgées de 6 à 13 ans, fertilisées ou non à raison de 224 kg·ha^{-1} d'urée, sur le diamètre moyen de la plus grosse branche à hauteur de poitrine (DPGBHP). Le DPGBHP est une mesure de terrain simple et non destructive qui est reliée aux indices de nodosité des billes utilisés pour mesurer la qualité des billes dans les études de rendement en produits. Le modèle [1] était efficace pour prédire le DPGBHP moyen (erreur quadratique moyenne = 2,80, r_{adj}^2 = 0,84) en n'utilisant comme variable que la station, le coefficient de distribution initiale des tiges et le traitement. Le modèle [2], qui n'utilisait que des variables moyennes prises sur les arbres, a amélioré le pouvoir prédictif du modèle [1] tout en étant plus simple. Cependant, le modèle [3], qui utilisait une combinaison des deux groupes de variables, a donné les meilleurs résultats. Le modèle [4] a prédit avec succès le DPGBHP moyen à partir de variables pouvant être mesurées avec le LIDAR, un instrument de télédétection à haute résolution. Puisque l'âge auquel la cime vivante passe au-dessus de la hauteur de poitrine est une variable importante de certains modèles, le modèle [5] a été mis au point pour prédire à quel âge survient le passage de la cime vivante au-dessus de la hauteur de poitrine. Cette étude a montré que le DPGBHP moyen des plantations de douglas de Menzies peut être estimé à l'aide de variables provenant de modèles de croissance à l'échelle du peuplement ou de la télédétection, ce qui en fait un bon indicateur qui peut facilement être mesuré et vérifié sur le terrain.

[Traduit par la Rédaction]

Introduction

Tree branches become knots within the stem that reduce product grade recovery and associated value. For example, when juvenile wood[2] in a log is 25%, recovery of high value 2100f machine-stress-rated (MSR) grade Douglas-fir (*Pseudostuga menziesii* (Mirb.) Franco var. *menziesii*) lumber dropped from 45% to 5% as the "largest limb average diameter" (LLAD) of logs increased from 13 mm (0.5 in.) to 38 mm (1.5 in.) (Fahey et al. 1991). LLAD, also known as "branch index" (BIX), is obtained by averaging the diameter of the largest knot in each of the four lengthwise faces of a log. Although recovery of MSR lumber varies with juvenile wood percentage, the importance of juvenile wood becomes progressively less important as LLAD increases. Similar losses in grade yield with increasing LLAD occur for veneer and visually graded lumber (Fahey et al. 1991), and similar results have been found for other species (Zhang et al. 2002). Numerous and (or) large diameter knots also reduce yield of moldings and cuttings when lumber is remanufactured by value-added industries, impact appearance values, and reduce pulp yield and increase pulping cost. These yield and grade losses translate into substantial losses in log and tree value (Aubry et al. 1998). Consequently, measures of knotti-

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[2]Based on the first 20 growth rings from the pith.

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ness are commonly incorporated in the valuation and grading of trees and logs. For example, Douglas-fir log grades (Northwest Log Rules Advisory Group (NWLRAG) 1998) and sorts (Bowers 1997) have a knot diameter resolution of 13 mm (0.5 in.), and some also have a restriction on the number of knots in each log quadrant. Although log and product grading and sorting use discrete knot diameter classes, it should be stressed that product grade recovery and value are a continuous function of LLAD (Fahey et al. 1991; Aubry et al. 1998), and any change in LLAD has an effect.

Branch development is a complex process influenced by physiological age of the tree and branch. In even-aged plantations, a branch at the top of a tree is initially in full sunlight and relatively free from competition for light regardless of stand density. Branch diameter growth rate declines with age because of a combination of (*i*) shading by younger, higher branches as its depth into the crown increases, (*ii*) hormonal control of its growth by these higher branches and the terminal shoot, (*iii*) increased shading by neighboring trees, (*iv*) reduced production of carbohydrates to sustain respiratory demand of living tissue leaving less available for new diameter growth, and (*v*) more difficult water transport with diminishing production of new conductive earlywood tissue (Kershaw et al. 1990; Protz et al. 2000). As these factors act over time, the branch eventually ceases growing and dies, and the live crown base rises. Researchers have found that branch diameter growth is primarily dependent on age and can be successfully modeled as a negative exponential function of branch age (Kershaw et al. 1990; Makinen 1999). Using the concept of allometry, branch diameter growth also has been modeled in relation to stem diameter growth (Makinen 1999; Briggs et al. 2004). Branches are commonly viewed as having two distinct regions; the initial region when it was alive and its wood grain is intergrown with that of the main stem (sound knot, live knot, or intergrown knot), followed by the region after branch death, when there is no growth connection between stemwood and the branch, and the stem is merely growing over the dead branch (unsound knot, dead knot, or encased knot). The period while the branch is alive is referred to as its longevity and depends on factors driving crown recession up the stem. The time after crown recession and branch death until the branch is self-pruned by the tree varies up to 80 years or more in Douglas-fir (Kotok 1951).

The basic patterns of branch growth and size are modified by site quality and silvicultural treatments, and many studies have examined their influences on various indices of branch diameter of trees. These indices include LLAD or BIX (DeBell et al. 1994; Grotta et al. 2004), mean of the five largest diameter branches (Ballard and Long 1988), or mean diameter of all branches (Grah 1961) of one or more log segments; the mean of the five largest diameter branches (Zhang et al. 2002) or mean diameter of all branches (Baldwin et al. 2000; Albaugh et al. 2006) of the entire tree; or the mean or largest branch diameter at breast height (Johansson 1992; Pape 1999). Regardless of the branch index used, studies indicate that larger branches occur on trees in stands planted at wider spacings (Baldwin et al. 2000; Zhang et al. 2002), that have been thinned (West 1998; Baldwin et al. 2000), and that developed lower stocking through natural mortality (Ballard and Long 1988; DeBell et al. 1994). Others have found that branch diameter is increased by fertilization (West 1998; Albaugh et al. 2006) and higher site quality (Tombleson et al. 1990).

Other studies developed crown profile models consisting of the vertical distribution, length, diameter, angle, etc., of individual branches (Makinen and Colin 1998; Maguire et al. 1999). These crown profile studies differ in several respects. Some modeled the largest, some modeled the mean, and some modeled all branches in each whorl. Some considered live branches only, while others considered both live and dead branches. Some do and some do not model sensescence, death, and self-pruning of branches, the live and dead knot portions of each branch, and self-pruning and occlusion. None of these studies appear to model the diameter of a branch as would be observed at the stem surface after it died and is being encased by subsequent stem growth. The dead branch diameter observed on the surface of a tree or log becomes progressively smaller with time because of taper, shrinkage due to moisture loss, and possible shedding of bark. Models that do not account for diminishing branch diameter measured on the stem surface after branch death are likely to overestimate log quality branch indices such as LLAD, which would cause biased estimates of product value from recovery studies (Fahey et al. 1991).

Although most studies examined branch diameter of trees growing in pure, even-aged stands, some have examined mixed stands and the effect of species mix and density on the branching of the subject species. Grotta et al. (2004) examined pure and mixed stands of Douglas-fir with red alder (*Alnus rubra* Bong.) planted simultaneously or with a 5 year delay and found that the LLAD of the 5.2 m butt log in Douglas-fir trees was greatest in its widest pure stand spacing, and that simultaneously planting alder with Douglas-fir produced the smallest LLAD. Garber and Maguire (2005) examined the vertical branch diameter profiles of spacing trials of a mix of lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. *latifolia* Engelm.) and ponderosa pine (*Pinus ponderosa* Dougl. ex P. & C. Laws.) and a mix of grand fir (*Abies grandis* (Dougl. ex D. Don) Lindl.) and ponderosa pine. They found that while tree variables were able to account for most stand conditions, models that included treatment variables representing spacing and species mix were superior.

Since changes due to site, silviculture, and species mix alter tree size, one could hypothesize from allometry that there would be no effect of these factors on branch diameter, if differences in tree size are first taken into account. This hypothesis is supported by many of the crown profile studies, which found that, while stand and site variables can be used to predict branch characteristics, models exclusively using appropriate tree variables, such as DBH, total height, and crown length, work just as well (Maguire et al. 1999; Vestol et al. 1999). However, few studies were designed to specifically test site, silvicultural treatment, and species effects on branch diameter over a broad range of conditions. Some recent studies suggest opposing conclusions regarding the allometry hypothesis. Grotta et al. (2004) found no differences due to density or species mix on the LLAD of Douglas-fir after adjusting for differences in DBH, therefore supporting those who found that only tree variables are needed. In contrast, Garber and Maguire (2005) found that while tree variables accounted for most of the differences in branch

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Table 1. Precommercially thinned and subsequent treatments on Stand Management Cooperative (SMC) type I Douglas-fir installations.

No.	Treatment type	PCT definition	Regime after PCT
1	ISPA	No PCT, leave 100% of initial stems per hectare (ISPA)	No thin, no fertilization
2	ISPA/2	PCT to 50% of ISPA	No thin, no fertilization
3	ISPA/4	PCT to 25% of ISPA	(*a*) No thin, no fertilization
			(*b*) No thin, add 224 kg·ha^{-1} N as urea at establishment and every 4 years
4	ISPA	No PCT, leave 100% of ISPA	Thin: RD 55 → RD 35, no fertilization
5	ISPA/2	PCT to 50% of ISPA	(*a*) Thin: RD 55 → RD 35, no fertilization
			(*b*) Thin plus add 224 kg·ha^{-1} N as urea at establishment and every 4 years
6	ISPA	No PCT, leave 100% of ISPA	(*a*) Thin: RD 55 → RD 35; RD 55 → RD 40; RD 60 → RD 40; . . ., no fertilization
			(*b*) Thin plus add 224 kg·ha^{-1} N as urea at establishment and every 4 years
7	ISPA	No PCT, leave 100% of ISPA	Thin: RD 45 → RD 30; RD 50 → RD 35; RD 55 → RD 40; . . ., no fertilization

Note: PCT, precommercial thinning; ISPA, initial stems·ha^{-1} present at establishment age before PCT; and RD, Curtis' relative density (Curtis 1982).

characteristics, models that also included treatment variables were superior.

While modeling the diameter of branches had advanced greatly from relatively simple descriptive methods of early studies to sophisticated crown profile models, a number of issues and questions remain. The various branch diameter indices developed in early studies are not consistent with each other nor with knot measures used in log grades and recovery studies. Except for the few studies that measured knots at the breast height level of trees, others collected knot data along the stem using either specialized pole calipers, ladders, or tree climbing, and others obtained data from felled trees and logs. Furthermore, none of the studies connect the index and the profile approaches. Issues for forest managers and other users concern the use of destructive sampling, relevancy of index models, and practicality, safety, and cost of obtaining appropriate data. While some have developed linkages among crown profile, growth and yield, and product conversion simulation models, these models are not widely available, and little has been done to provide means by which a manager can obtain routine knot data in the field to calibrate or verify them. Consequently, there is a need for a direct, simple, nondestructive field measurement of branch diameter of trees that can be related to log quality, product recovery studies, and provide linkages to crown, growth, and conversion models. Although four studies measured the knot diameters at breast height of trees, they did not investigate linkages to log quality indices used in product recovery studies. Recent studies of Douglas-fir (Briggs et al. 2005, 2007) found that the LLAD of the first log in trees can be predicted from the diameter of the largest limb in the breast height region (DLLBH) providing the first evidence of this link.

Although DLLBH is simple to measure, visits to field plots may be too expensive, too sparse, and too infrequent for planning, monitoring, and other purposes. Consequently, it would be desirable to develop models to predict mean DLLBH for use with growth and yield models to improve understanding of how silvicultural regimes affect DLLBH. Coupling these models with the DLLBH–LLAD models would provide an extension to the quality of the first log. This information could assist in harvest and silvicultural planning. Since both stand-level and individual-tree level growth and yield models are commonly used, DLLBH models should be developed for use with each of these model types. Light detection and ranging (LIDAR), a high-resolution remote sensing technology, has recently developed as a technique for measuring height, crown, and density attributes of forest stands (Reutebuch et al. 2005). Since these attributes are frequently used in branch diameter models, it may be possible to develop models based on LIDAR to estimate DLLBH. This would form the basis for mapping DLLBH or first log quality of stands in geographic information system to assist planning across landscapes.

Objectives

The first objective of this study was to develop models for DLLBH of Douglas-fir trees. Model [1] will use treatment, site, and stocking variables only; we expect to find that DLLBH is increased by thinning and fertilization treatment, increases with higher site index, and decreases with increasing stand density. Model [2] will use mean tree variables such as DBH, crown measures, and height; we expect that mean tree variables act as reasonable surrogates for site, stocking, and treatment variables and that model [2] will perform as well as model [1]. Model [3] will use a combination of treatment, site, stocking, and mean tree variables; we expect that model [3] will improve on models [1] and [2]. The second objective was to develop model [4] for DLLBH with variables that can be measured using LIDAR, augmented with stand information, such as site index and treatment history, and that a manager would have from stand records. Models [1]–[4] predict mean DLLBH of a stand of trees; a subsequent report will present models for predicting DLLBH of individual trees.

Experimental

Sample installations and data collection

Between 1986 and 1995, the Stand Management Cooperative (SMC)[3] created 30 Douglas-fir type I installations that were established in existing stands several years after plant-

[3] A consortium of landowners and research institutions in the Pacific Northwest formed in 1985 to provide high-quality data on the long-term effects of silvicultural treatments on growth and yield, wood quality, and other forest services.

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Table 2. Characteristics of the nine type I installations with the density management – fertilization experiment.

Installation	County and state	Elevation (m)	Slope (%)	Aspect[a]	Site index 50^b (m)	Site index 30^c (m)	Planting date	No. of trees·ha^{-1} at estab.[d]	Estab. year	Age from planting at estab. (years)	Latest branch measurement year	Age to last branch measurement (years)
704, Ostrander Road	Cowlitz, Washington	183	20	270	37	25	Jan. 1974	1420	1987	13	2003	29
705, East Twin Creek	King, Washington	823	30	180	27	23	Jan. 1976	1729	1987	11	2003	27
708, Copper Creek	Lewis, Washington	274	5	999	38	28	Jan. 1981	1062	1988	7	2004	23
713, Sauk Mountain	Skagit, Washington	242	5	180	37	27	1978	1329	1988	10	2004	26
718, Roaring River	Linn, Oregon	335	10	888	39	28	Jan. 1982	988	1989	7	2001	19
722, Silver Creek Mainline	Marion, Oregon	671	10	270	37	22	Feb. 1977	1359	1989	12	2001	24
725, Sandy Shore	Jefferson, Washington	168	0	999	37	27	Dec. 1980	1112	1990	10	2002	22
726, Toledo	Lincoln, Oregon	91	10	225	41	28	Jan. 1984	894	1990	6	2002	18
736, Twin Peaks	King, Washington	183	40	270	37	28	March 1984	1112	1992	8	2004	20
Mean										9		23

[a]Degrees azimuth: 888, variable aspect; 999, flat, no aspect.
[b]Site index 50, based on breast height age, is from King (1966).
[c]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 from the plot measurement closest to age 20 years.
[d]Mean of the four initial stems per hectare (ISPA) plots on each installation.

ing, at a time close to the onset of inter-tree competition. At each installation, plots were located to ensure as similar slope, aspect, and other conditions as possible. Four plots were randomly chosen to remain at the initial stems per hectare (ISPA) present at establishment; of these, three were assigned thinning prescriptions based on relative density (Curtis 1982). Two randomly chosen plots were precommercially thinned (PCT) with a systematic thinning to one-half of the initial stems per hectare (ISPA/2); one of these was assigned a thinning prescription based on Curtis' RD. The remaining plot was precommercially thinned (PCT) with a systematic thinning to one-fourth of the initial stems per hectare (ISPA/4). As examples, an installation with 1200 stems·ha^{-1} at plot establishment had ISPA = 1200, ISPA/2 = 600, and ISPA/4 = 300, whereas another installation with 1600 stems·ha^{-1} at plot establishment had ISPA = 1600, ISPA/2 = 800, and ISPA/4 = 400, etc. Because of the systematic thinning, the size of trees in the residual stand was not significantly changed. On nine installations, three additional plots, corresponding with thinning treatments 3, 5, and 6 in Table 1, were created and received 224 kg·ha^{-1} (200 lb/acre) nitrogen (N) as urea at plot establishment and every 4 years thereafter. Each plot is 0.47 ha (1.15 acres) and contains a 0.2 ha (0.5 acre) permanent measurement sample plot surrounded by a 9.3 m (30.5 ft) buffer.

These nine installations with six plots each (Table 2) are the basis for this study and 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 thinning, and fertilization was randomly assigned. Installations were planted between 1974 and 1984, and plots were established between 1987 and 1992 when they were 6–13 years old (mean = 9 years). King's 50 year breast height (BH) age site index (King 1966), provided by landowners at establishment, ranged from 27 to 41 m with seven of nine in site class II. Using the trees present on each plot, we calculated a 30 year, age from seed, site index (Flewelling et al. 2001) with a range from 23 to 28 m.

In 1999, the SMC initiated a procedure to measure DLLBH on plots in its field research installations. 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. These DLLBH measurements, obtained on approximately 40 trees per plot, represent a broad range of sites and treatment conditions, and provide a unique data set to develop DLLBH models.

Table 3 defines the variables, units of measure, and symbols for variables used in the analysis. The data set consists of six plots from nine installations (54 plots total) on which a total of 2257 trees have DLLBH branch measurements. Although most installations have been measured more than one time since implementation of the BH branch procedure, we used the single most recent DLLBH from each tree, collected during 2002–2005, when the installations ranged in age from 22 to 32 years old from seed. By this time virtually all BH branches were dead. For crown recession, we used the time since establishment until the first 4 year measurement, when the crown base exceeded BH, as the time when the largest BH branch changed from live to dead. The crown base is defined as the lowest whorl in which live

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Table 3. Definition of variables used in plot (stand) level models.

Variable	Description
Dependent	
DLLBH	Diameter of the largest limb in the breast height (BH) region of a tree (mm)
Independent (treatment effects)	
ISPA1	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
ISPA2	
ISPA4	
FERT	Binary (0,1) variable. Code = 0 if plot was not fertilized; code = 1 if fertilized with 224 $kg \cdot ha^{-1}$ (200 $lb \cdot acre^{-1}$) N as urea at establishment and every 4 years since
Independent (plot conditions)	
ISTEMS	Average $trees \cdot ha^{-1}$ present at establishment on the entire installation before spacing to the ISPA densities
IRD	Curtis' relative density at establishment before spacing to the ISPA densities; plot basal area ($m^2 \cdot QMD^{-1}$, $cm^{1/2}$)
SI_{30}	Flewelling's 30 year site index calculated from plot data closest to age 20 years
PSTEMS	No. of $trees \cdot ha^{-1}$ present after establishment respacing on each plot
CSTEMS	No. of $trees \cdot ha^{-1}$ present at the time of DLLBH measurement
PRD	Curtis' relative density at establishment after respacing each plot; plot basal area (m^2/QMD^{-1}, $cm^{1/2}$)
Independent (time of crown recession above BH)	
*Y*_Until_CR	Elapsed years from spacing at establishment until the crown receded above BH (used first measurement cycle when crown height > BH)
*Y*_Since_CR	Elapsed years since the crown receded above BH until the latest BH branch measurement
*Y*_total	Sum of *Y*_Until_CR and *Y*_Since_CR
Independent (tree variables per plot)	
DBH	Diameter at breast height (cm)
QMD	Quadratic mean DBH (cm)
HT	Total height (m)
HT40	Average height of the 40 largest trees by DBH (m)
HCB	Height to crown base (m)
HT/DBH	Ratio of total height to DBH
CL	Crown length = HT – HCB (m)
CR	Crown ratio = 1 – HCB/HT

[a]Arithmetic mean, except as noted.

branches are in three of the four quadrants of the crown. The 4 year measurement interval, definition of height to the crown base, and location of the first whorl above BH combine to cause a discrepancy between the actual year of mortality of the largest BH branch and our crown recession measure. We did not attempt to interpolate the year of largest BH branch death within the 4 year measurement interval. The number of years until crown recession above BH is calculated from the year of plot establishment until the first measurement year when crown recession was above BH. This differs from branch longevity, which, as explained earlier, is the time between branch initiation and death. The number of years since crown recession above BH, and hence, branch death, is calculated as the time between the first measurement year when crown recession was above BH and the year when DLLBH was measured.

Model specification

Objective 1 investigated three models for plot mean DLLBH using treatment, site, and stocking variables only (model [1]); mean tree variables such as DBH, crown, and height variables only (model [2]); and a combination of treatment, site, stocking, and mean tree variables (model [3]). Variants of models [2] and [3] specified use of either arithmetic mean DBH and height or quadratic mean diameter (QMD) and average height of the 40 largest DBH trees (HT40). These variants were developed since some growth models use QMD and HT40.

Based on the literature, it is reasonable to propose that mean DLLBH at establishment would be greater on plots with lower prethinning density, that thinning would promote increased growth and longevity of BH branches thereby increasing DLLBH, and that fertilization would promote additional growth. It is also likely that DLLBH at establishment and subsequent response may vary according to site quality with larger DLLBH expected on higher sites. Finally, since BH branches died at some time between establishment of the treatment plots and measurement of DLLBH, time until and after the crown receded above BH may also be important in representing the negative effect of measuring diameter on dead, tapered branches at the stem surface. Consequently, model [1*a*] was specified to include ISTEMS and IRD, the average pre-PCT density conditions on each installation at the age of plot establishment. Variables

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ISPA1, ISPA2, and ISPA4 are categorical variables representing the levels of PCT applied (i.e., no PCT, leave one-half of the trees, or leave one-quarter of the trees), and FERT is a categorical variable representing presence or absence of the fertilization regime. ISI_{30} represents the average site index of the installation, and AGE represents the stand age at the time of DLLBH measurement. Model [1*a*] also included variables associated with time (*Y*) before and after crown recession above BH (*Y*_Until_CR, *Y*_Since_CR, and *Y*_Total); two-way interactions; and error.

$$[1a] \qquad \overline{\mathrm{DLLBH}} = \mu + \mathrm{ISPA} + \mathrm{FERT} + \{\mathrm{ISTEMS}, \mathrm{ISI}_{30}, \mathrm{IRD}, \mathrm{AGE}\} + \{Y\_\mathrm{Until\_CR}, Y\_\mathrm{Since\_CR}, Y\_\mathrm{Total}\} + (\mathrm{interactions}) + \mathrm{error}$$

where DLLBH and μ refer to the overall mean; ISPA and FERT are treatment effect (fixed; ISTEMS, ISI_{30}, IRD, and AGE are the initial stand condition covariates; *Y*_Until_CR, *Y*_Since_CR, and *Y*_Total, are the crown recession covariates; (interactions) refers to two-way interactions between the variables; and error refers to random error.

Because of variability in pretreatment density between installations and between plots within an installation, model [1*b*] presents an alternative approach for specifying initial treatment plot conditions. The installation-wide average stocking measures ISTEMS and IRD and categorical PCT level variables in model [1*a*] are replaced with the actual density present on each plot (PSTEMS and PRD) immediately following the PCT. Furthermore, the installation-wide average site index was replaced by the individual treatment plot site indices (SI).

$$[1b] \qquad \overline{\mathrm{DLLBH}} = \mu + \mathrm{FERT} + \{\mathrm{PSTEMS}, \ \mathrm{SI}_{30}, \mathrm{PRD}, \ \mathrm{AGE}\} + \{Y\_\mathrm{Until\_CR}, Y\_\mathrm{Since\_CR}, Y\_\mathrm{Total}\} + (\mathrm{interactions}) + \mathrm{error}$$

Many previous studies concluded that branch diameter can be modeled based on tree variables alone. Consequently, model [2] considered the arithmetic mean of measured variables DBH, total height, and height to crown base and calculated variables crown length, crown ratio, and height/DBH ratio. Model [2] regards average tree dimensions as reasonable surrogates for the density management and fertilization regime under the assumption that these treatments largely determine the average DBH, height, and crown length combinations found on the treatment plots.

$$[2] \qquad \overline{\mathrm{DLLBH}} = \mu + \{\overline{\mathrm{DBH}}, \overline{\mathrm{HT}}, \overline{\mathrm{HCB}}, \overline{\mathrm{CL}}, \overline{\mathrm{CR}}, \overline{\mathrm{HT/DBH}}\} + (\mathrm{interactions}) + \ \mathrm{error}$$

where $\overline{\mathrm{DBH}}$ is the mean diameter at breast height, $\overline{\mathrm{HT}}$ is the mean total tree height, $\overline{\mathrm{HCB}}$ is the mean height to crown base, $\overline{\mathrm{CL}}$ is the mean crown length, $\overline{\mathrm{CR}}$ is the mean crown ratio, and $\overline{\mathrm{HT/DBH}}$ is the mean total height to DBH ratio.

Since growth models often use QMD and HT40, a variant of model [2] substitutes these treatment plot variables for arithmetic mean DBH and total height.

Since other studies concluded that the best branch models combine tree, stand, and treatment variables, model [3] combined the treatment and stand variables of models [1*a*] or [1*b*] with the mean tree variables of model [2]. As in model [2], a variant substituted QMD and HT40 for mean DBH and total height in model [3].

Objective 2 investigated model [4] using variables that can be measured by LIDAR, mean total height, mean crown variables, and current tree count in stems per hectare, to predict mean DLLBH. A model [4] variant augmented these LIDAR variables with site index and treatment variables that could be obtained from stand records.

$$[4] \qquad \overline{\mathrm{DLLBH}} = \mu + \{\overline{\mathrm{HT}}, \overline{\mathrm{HCB}}, \overline{\mathrm{CL}}, \overline{\mathrm{CR}}, \overline{\mathrm{CSTEMS}}\} + \{\mathrm{FERT}, \ \mathrm{SI}_{30}\} + (\mathrm{interactions}) + \ \mathrm{error}$$

where $\overline{\mathrm{HT}}, \overline{\mathrm{HCB}}, \overline{\mathrm{CL}}, \overline{\mathrm{CR}}$, and $\overline{\mathrm{CSTEMS}}$ are the LIDAR measurements and FERT and SI_{30} are the stand record information.

Models [1] and [3] include variables dependent on the age when the crown recedes above BH. Although age of crown recession above BH may be available from some growth models, it would be desirable to have a model to estimate it. We calculated the proportion (*P*) of trees with the live crown base above BH at plot establishment and at every subsequent remeasurement for the 54 plots, generating 241 observations. Model [5] is a logistic model based on the *P* data where the βs are the intercept and coefficients of predictor variables.

$$[5] \qquad P = \frac{e^{f(x)}}{1 + e^{f(x)}}, \qquad f(x) = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_2 X_2 + \beta_i X_i$$

where X_i are predictor variables; age of the stand at each remeasurement when *P* was calculated, SI_{30}, FERT, and stand density measures.

Analysis procedure

To estimate DLLBH, multiple regression analysis was used to analyze models [1]–[4]. As a nature of ecological data, the response is linked to many explanatory variables that are often correlated among each other, which causes spurious correlation (Graham 2003). Preliminary data analyses revealed that installations planted prior to 1980 were typically planted at higher densities and on lower quality sites than installations planted after 1980 (Table 2). These trends produced unexpectedly high correlations of the density variables and site index with stand age. Consequently, stand age was dropped from further analyses. Furthermore, since some variables are mathematically derived from others, e.g., CL = HT – HCB, we prohibited one member of the identity when the others were used.

Analysis of each model proceeded by first examining Mallow's Cp and Akaike's corrected information criterion (AIC_c) (Hurvich and Tsai 1989) of all possible sets of the independent variables. Variable sets that were best according to these criteria were compared with the models selected from variable selection method using backward and stepwise selection. The variable selection used significant level criteria at 0.15 for entering and 0.05 for staying. The selected model is the one that has lowest AIC_c. Each model was ex-

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Table 4. Parameter estimates and standard errors for model [1].

Variable	Estimated value	SE
Model [1*a*] (RMSE = 2.94 and r_{adj}^2 = 0.82)		
Intercept	10.5653	7.6601
ISPA/1[a]	0	—
ISPA/2[a]	3.6238	1.0663
ISPA/4[a]	6.0451	1.3521
FERT[a]	2.1295	0.8035
ISTEMS	–0.007 314	0.001 995
ISI_{30}	1.5272	0.2723
IRD	2.1007	0.8438
*Y*_SINCE_CR	–0.8668	0.1695
Model [1*b*] (RMSE = 2.80 and r_{adj}^2 = 0.84)		
Intercept	23.4409	0.5745
FERT[a]	2.3708	0.7682
PSTEMS – 685.0	–0.007 552	0.001 167
SI_{30} – 26.5	1.0522	0.1701
(PSTEMS – 685.0) (SI_{30} – 26.5)	–0.001 100	0.000 481
*Y*_SINCE_CR – 5.0	–0.8253	0.1272
(PSTEMS – 685.0) (*Y*_SINCE_CR – 5.0)	0.000 464	0.000 224

[a]Binary (0,1) variable; ISPA1 is the default model with ISPA2 = 0 and ISPA4 = 0.

amined with main effects only and then with two-way interactions. When interactions were considered, hierarchy was enforced, and the data were centered; a transformation in which each predictor value is subtracted from its mean before fitting the regression model. Centering decreases correlation among the individual predictors and their product terms and makes coefficients of predictors more interpretable (Jaccard and Turrisi 2003). Goodness-of-fit was assessed on the basis of the smallest AIC_c examination of the residuals, and the variance inflation factor (VIF) for each variable was checked for possible collinearity. In cases where retaining an additional variable produced very minor improvement in AIC_c, we opted for the model with fewer terms. For each regression model, normality of the distribution of residuals, heteroscedasticity, and multicollinearity were checked using the Shapiro–Wilk test, VIFs, and by visual plots. All model [1]–[4] analyses were performed using SAS version 9.1 (SAS Institute Inc. 2003).

Since the repeated measurements lead to longitudinal data, model [5] parameter estimates were obtained using (*i*) the generalized estimating equation (GEE) method, which accounts for correlation between repeated measurements (Horton and Lipsitz 1999) and (*ii*) the bootstrap method, which took repeated random samples of one measurement per plot to obtain empirical distributions for the parameter estimates (Efron and Tibrishani 1993). The model [5] GEE variant was estimated using the SAS version 9.1 GENMOD procedure with the working correlation matrix as both unstructured and exchangeable (Thies et al. 2006), and the bootstrap variant was estimated using the bootstrap command in STATA version 10 (StataCorp 2007).

Validation

To test the models, a hold-out procedure was used in which each model was estimated using eight of the nine installations and the treatment plots on the held out installation were estimated from the model based on the other eight. This procedure was repeated until all possibilities were examined. As a further test, two other type I installations were randomly chosen, one from Oregon and one from Washington, and mean DLLBH of plots on these installations were compared with predictions from the models.

Results and discussion

Table 4 presents model [1*a*] (RMSE = 2.93 and r_{adj}^2 = 0.82), which used ISTEMS and IRD to account for average density conditions just prior to application of PCT; ISPA1, ISPA2, and ISPA4 as indicators of the different PCT levels; FERT to indicate if the fertilization regime was applied; ISI_{30} to account for average site quality between installations; and *Y*_SINCE_CR. Fewer initial trees per hectare (ISTEMS), further reduction of density to one-half or one-fourth by the PCT, fertilization, and higher site quality lead to larger mean DLLBH. For a given site and ISTEMS condition, mean DLLBH is greater when initial relative density (IRD) is greater. Relative density, based on QMD and basal area per hectare, takes into account differences in average tree size for the same tree count per unit area. A larger IRD implies trees that were already larger at establishment and therefore would be expected to have larger diameter branches. Mean DLLBH is smaller if more time has elapsed since crown recession, a reflection of measuring diameter further out on a tapered, dead branch. No two-way interactions were significant in model [1*a*]. Model [1*a*] variant agrees with other studies that found that branch diameter is increased by lower initial stand density and thinning conditions (e.g., Baldwin et al. 2000; Zhang et al. 2002). However, model [1*a*] differs from many other studies that only used trees per hectare as the stand density measure. Model [1*a*] found that the combination of both trees per hectare and relative density, which incorporates stand basal area and QMD, is important. Model [1*a*] agrees with others (West 1998; Albaugh et al. 2006), who found that branch diameter was increased by fertilization and increases with

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Table 5. Parameter estimates and standard errors for model [2].

Variable	Estimated value	SE
Model [2*a*] (RMSE = 2.52 and r_{adj}^2 = 0.87)		
Intercept	25.5993	0.3660
DBH – 26.9	1.2578	0.077 60
HT – 18.8	–1.9725	0.1625
(DBH – 26.9)(HT – 18.8)	–0.092 32	0.034 42
Model [2*b*] (RMSE = 2.37 and r_{adj}^2 = 0.88)		
Intercept	25.1105	0.3284
QMD – 27.5	1.0572	0.070 57
HT40 – 20.4	–1.7097	0.1229
(QMD – 27.5)(HT40 – 20.4)	–0.090 19	0.029 67

higher site index (Tombleson et al. 1990). Because branches were dead when measured, the time since branch death is also important and shows a steady decrease of approximately 0.9 mm·year^{-1} in dead branch diameter at the stem surface. Since product recovery study results are continuous over log branch index changes (Fahey et al. 1991), taking this into account could be important in establishing linkage between DLLBH, log branch index, and product recovery and value.

Whereas the model [1*a*] used average pretreatment density and average site index for each installation with PCT level indicator variables for the treatment plots, model [1*b*] (RMSE = 2.80 and r_{adj}^2 = 0.84) used actual density conditions (PSTEMS and PRD) on each plot immediately following PCT and the actual site index of each plot. In comparison with model [1*a*] (Table 4), model [1*b*] only produced a modest improvement, but it has fewer variables. Unlike model [1*a*], model [1*b*] does not include relative density but does have significant two-way interactions. In other respects, model [1*b*] is similar in interpretation to model [1*a*]; fertilization, higher site quality, and lower densities produced by PCT lead to larger mean DLLBH. The negative interaction between site index and density indicates that mean DLLBH decreases disproportionately faster on higher sites as density increases as compared with lower sites. In addition, there is a positive interaction of density after PCT with time since the crown receded above BH. Although the average tree size was not altered by the systematic PCT, it is likely that BH branches of residual trees with PCT to low densities survived longer and grew larger than BH branches of residual trees where PCT left higher densities. Furthermore, stem diameter growth in the low density stands would be greater, so the dead BH branches would be grown over faster in lower density stands. The interaction indicates that, as time since crown recession increases, the decrease in branch diameter is relatively less in stands where PCT left low rather than high stand densities.

Table 5 presents model [2*a*] (RMSE = 2.52 and r_{adj}^2 = 0.87), which specified only arithmetic mean tree variables for each treatment plot, and model [2*b*] (RMSE = 2.37 and r_{adj}^2 = 0.88), which substituted QMD and HT40 for arithmetic mean DBH and total height. Compared with model [1], model [2] has fewer variables and reduced RMSE by about 10%–15%. This result is consistent with others (e.g., Maguire et al. 1999; Vestol et al. 1999) who found that tree descriptors alone perform at least as well as stand and treatment variables as predictors of branch diameter. Stands with larger mean DBH trees have larger mean DLLBH; however, mean DLLBH decreases as mean total height increases. Greater height is suggestive of greater distance between BH and the crown base leading to a negative effect on mean DLLBH due to more elapsed time to grow over dead branches. The interaction suggests that the decrease in mean DLLBH for a given DBH depends on height; DLLBH decreases faster for taller trees of a given DBH. The ratio of height to diameter (HT/DBH) was not significant, nor were any of the crown variables. Since model [2] does not include any of the crown variables, mean DBH (or QMD), mean total height (or HT40), and their interaction apparently act as

Table 6. Parameter estimates and standard errors for model [3].

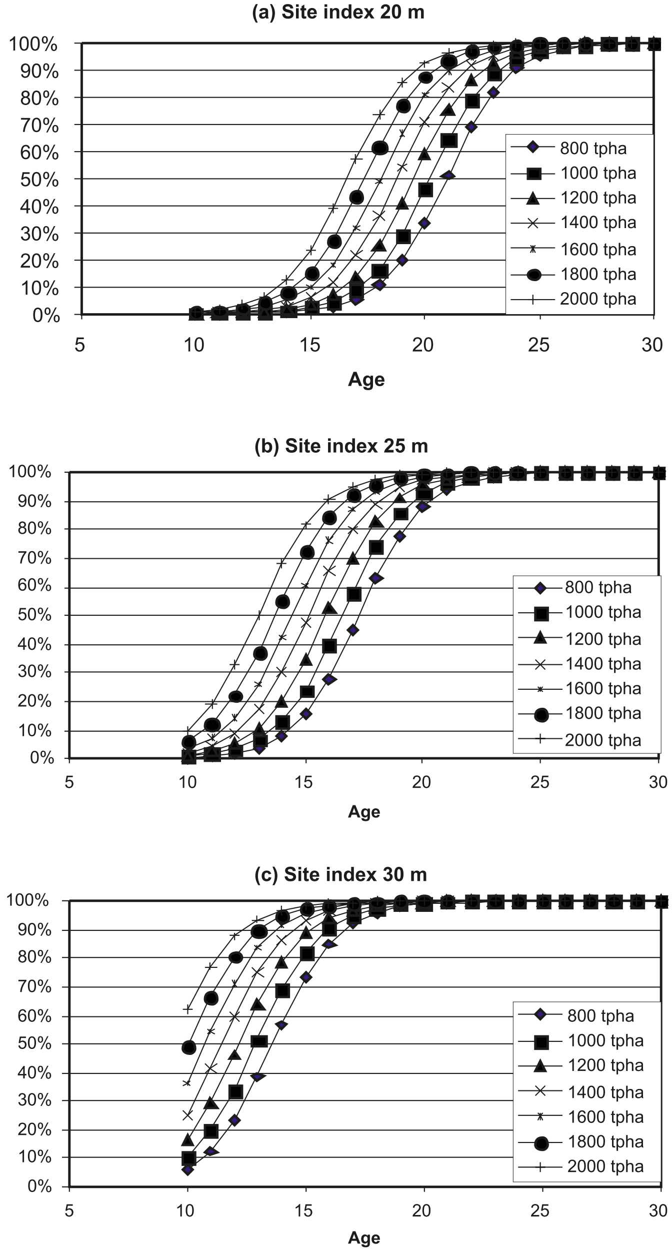
Variable	Estimated value	SE
Model [3*a*] (RMSE = 1.99 and r_{adj}^2 = 0.92)		
Intercept	25.5109	0.2906
DBH – 26.9	1.0276	0.0903
HT – 18.8	–1.2942	0.2381
(DBH – 26.9) (HT – 18.8)	–0.068 83	0.027 72
SI_{30} – 26.5	0.7390	0.1328
*Y*_SINCE_CR – 5.0	–0.3634	0.1392
Model [3*b*] (RMSE = 1.98 and r_{adj}^2 = 0.92)		
Intercept	25.1615	0.2769
QMD – 27.5	0.9174	0.0758
HT40 – 20.4	–1.1891	0.2054
(QMD – 27.5)(HT40 – 20.4)	–0.068 88	0.025 29
SI_{30} – 26.5	0.6610	0.1379
*Y*_SINCE_CR – 5.0	–0.3154	0.1446
Model [3*c*] (RMSE = 2.19 and r_{adj}^2 = 0.90)		
Intercept	1.2199	7.1925
DBH	1.0058	0.1073
HT	–1.486 67	0.2296
CR	0.0943	0.0402
SI_{30}	0.7241	0.1509
Model [3*d*] (RMSE = 2.10 and r_{adj}^2 = 0.91)		
Intercept	2.9273	7.0014
QMD	0.8785	0.0879
HT40	–1.2967	0.1837
CR	0.0878	0.0384
SI_{30}	0.7282	0.1432

Table 7. Parameter estimates and standard errors for model [4] (light detection and ranging, LIDAR).

Variable	Estimated value	SE
Model [4*a*] (RMSE = 4.06 and r_{adj}^2 = 0.66)		
Intercept	63.1488	4.6406
HT	–1.4104	0.2301
CSTEMS	–0.0227	0.002 65
Model [4*b*] (RMSE = 2.93 and r_{adj}^2 = 0.82)		
Intercept	6.4683	4.8331
HCB	–1.0991	0.1549
CSTEMS	–0.013 18	0.002 25
SI_{30}	1.2248	0.1732
FERT[a]	2.2937	0.8169

[a]Binary (0,1) variable.

Fig. 1. Percentage of trees in a stand with crown recession above breast height by site class, stand density, and stand age.



reasonable surrogates for changes in tree and crown geometry associated with the stand density and fertilization treatments.

Table 6 presents the model [3*a*] (RMSE = 1.99 and r_{adj}^2 = 0.92), which combined the mean tree descriptors and stand and treatment variables and model [3*b*] (RMSE = 1.98 and r_{adj}^2 = 0.92), which substituted QMD and HT40 for arithmetic mean DBH and total height. Compared with model [2], model [3] further reduced RMSE by about 15%–20% by including site index and time since crown recession as adjustments to tree geometry. The improvement of model [3] over models [1] and [2] is in agreement with Garber and Maguire (2005). Since *Y*_Since_CR is strongly correlated with CR (ρ = –0.88), models [3*c*] (RMSE = 2.19 and r_{adj}^2 = 0.90) and 3*d* (RMSE = 2.10 and r_{adj}^2 = 0.91) were

Table 8. Parameter estimates and standard errors for model [5].

Variable	Estimated value	SE
Intercept	–28.2600	3.4652
AGE	0.7360	0.0508
SI_{30}	0.5370	0.1016
PSTEMS	0.002 637	0.000 487

obtained when *Y*_SINCE_CR was excluded. Although slightly inferior to models [3*a*] and [3*b*], in models [3*c*] and [3*d*], no interactions were significant and the CR may be easier to measure than *Y*_SINCE_CR in many situations.

Table 7 presents model [4*a*], obtained when model [3] was restricted to consider only tree variables and stem count per hectare that can be obtained by LIDAR (Reutebuch et al. 2005). Model [4*a*] (RMSE = 4.06 and r_{adj}^2 = 0.66) includes total height and tree count, but is improved as shown in model [4*b*] (RMSE = 2.93 and r_{adj}^2 = 0.82) when the LIDAR variables are augmented by knowledge of site index and whether or not the stand had been fertilized. Apparently total height in model [4*a*] acts as a surrogate for site index, while total height and tree density act as surrogates for height to the crown base and, hence, time since crown recession above BH. Model [4*b*], which uses site index directly to account for differences in site productivity, replaced total height by height to the crown base, a better surrogate for distance and time since the crown receded above BH.

Since *Y*_SINCE_CR is a significant variable in models [1] and [3], the age when the crown receded above BH in a stand must be known to estimate this variable. Model [5], a logistic regression, was specified to predict the *P* of trees in a stand with the base of the live crown above BH. Estimates of parameters based on the GEE and bootstrap methods were very similar, but the sSEs of the bootstrap parameters were smaller. Table 8 presents the model [5] bootstrap version based on 1000 repeated samples. We chose the bootstrap over the GEE version, since others who have compared these methods have found that bootstrap models were superior (Park and Kim 2004; Shin et al. 2007) The function $f(x)$ in model [5] indicates that the proportion of trees in a stand with the live crown above BH increases with stand age, with greater crowding of trees expressed as higher number of trees per hectare, and with higher site index. Figure 1 presents model [5] over a range of ages and densities from 800 to 2000 trees·ha^{-1} for three site indices. Figure 1*b* indicates that at least 95% of trees on site 30 m land with 1400 trees·ha^{-1} have the base of the live crown above BH by age 15 years. If a manager wishes to predict mean DLLBH of a 25-year-old stand assuming these conditions, *Y*_SINCE_CR would be estimated as 11 years. Note that year 15 is included since it is the first year with the live crown above BH.

VIFs indicated no collinearity problems in the final models, there were no residual patterns, and the errors were normally distributed with homogeneous variance. This was further confirmed using the hold-out procedure. When the final models were used to predict mean DLLBH of treatment plots on two other type I installations, there was a tendency for the models to underpredict mean DLLBH; with the mean error ranging from 1 to 3 mm. However, differences between the RMSEs of the models and RMSEs of the pre-

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Table 9. Plot (stand) level statistics of dependent and independent variables (n = 54).

Variable	Mean	SD	Min.	Max.
DLLBH (mm)	25.3	6.95	12.7	43.3
ISTEMS (trees·ha^{-1})	1297	421.8	697	2550
IRD (m^2/ cm$^{1/2}$)	2.3	1.3	0.7	5.9
SI_{30} (m)	26.5	2.35	21.6	29.9
PSTEMS (trees·ha^{-1})	685	455.5	188	2096
CSTEMS (trees·ha^{-1})	504	2082	163	1077
PRD (m^2/ cm$^{1/2}$)	1.2	1.0	0.2	4.7
*Y*_Until_CR	9.3	3.01	4	16
*Y*_Since_CR	5.0	3.77	0	13
*Y*_total	14.3	2.02	12	17
DBH (cm)	26.9	4.75	18	38
QMD (cm)	27.5	4.66	19	39
HT (m)	18.8	2.43	16	25
HT40	20.4	2.76	16	27
HCB (m)	7.5	3.08	2.1	14.0
HT/DBH (cm·cm^{-1})	71.6	12.83	48	101
HT40/QMD	76.2	15.31	48	113
CL (m)	11.4	2.09	8	18
CR (%)	60.5	13.46	39.6	85.6

Note: See Table 3 for a definition of the variables.

dicted installations were within ±1 mm. Since the field measurements are taken to the nearest millimetre, these differences may be of little practical concern.

Management implications

The models developed in this study differ from previous studies in two key respects. First, this study focused on DLLBH, a simple nondestructive measurement that can be routinely and repeatedly taken from standing trees. This contrasts with measurements for knot indices and crown profiles obtained with specialized poles, ladders, and climbing standing trees or destructive sampling by felling to measure trees or logs. DLLBH could be easily incorporated into routine forest inventories and other stand assessments. Second, models from this study were developed for stand-level rather than individual-tree level predictions. Stand-level DLLBH models would be appropriate to use in conjunction with stand-level growth and yield models such as Douglas-fir simulator (DFSIM) (Curtis et al. 1981) or Tree Laboratory (TREELAB) (Pittman and Turnblom 2003). In practice, the choice among models [1]–[3] depends on objectives and information available. Model [5] could be used to estimate age of crown recession in models [1]–[3] when this is not available from the field measurements or a growth model. Model [4] indicates a potential and opportunity for estimating mean DLLBH of stands from remotely sensed measures based on LIDAR. Model [4] suggests that future research to directly relate LIDAR metrics with plot measurements of DLLBH will be successful. Using LIDAR-derived models for DLLBH, in combination with field plots, would permit mapping of mean DLLBH or first log quality across the mosaic of stands on a property in a GIS system. Such maps could assist managers in monitoring changes in quality, in planning silvicultural operations, and in harvest planning. Once DLLBH has been estimated, models relating tree DLLBH and log LLAD (Briggs et al. 2005, 2007) can be used to link product recovery and value studies (Fahey et al. 1991; Aubry et al. 1998). DLLBH can be easily assessed and monitored as stands develop using process capability analyses techniques (Briggs et al. 2005, 2007).

Conclusion

This study examined models used to predict the mean DLLBH of trees in Douglas-fir stands that had received PCT followed by thinning and fertilizer regimes starting at an early age (6–13 years). DLLBH is a direct, simple, nondestructive measurement that does not rely on felled trees or logs and therefore can be incorporated into forest inventory and other stand assessments.

- Objective 1 examined models for the prediction of mean DLLBH using only stand and treatment variables (model [1]), only mean tree variables (model [2]), and a combination of tree, stand, and treatment variables (model [3]). Model [1] found that wider spacing and fertilization each increased DLLBH, but this is dependent on site index and on the length of time since the crown recession above BH (branch death). Model [2] found that using just mean tree DBH and mean tree height was simpler and superior to model [1]. However, model [3] found that model [2] was improved with the inclusion of site index and knowledge of the time elapsed since the crown receded above BH, which can be estimated with the assistance of model [5].
- Objective 2 examined the potential of using remote sensing with LIDAR to estimate DLLBH. Model [4] found that combining variables that can be measured with LIDAR with information from stand records can successfully estimate mean DLLBH.

The reader should be cautioned to refer to Table 9 to avoid extrapolation beyond the range of data used in developing these models. Furthermore, since sufficient time had elapsed for the crown to recede above BH so all branches were dead, the models should not be used to predict DLLBH before the crown has receded above BH. Directions for future research include (*i*) extending these models to predict DLLBH for individual trees, (*ii*) to further explore the opportunity to predict DLLBH from LIDAR, (*iii*) examine the dynamics of the change in DLLBH as branches progress from live to dead, and (*iv*) determine if these models can be adjusted to predict the diameter of the largest branch at other fixed heights.

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