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SECOND-LOG BRANCH SIZE COMPARISON BETWEEN EVEN-AGED AND MULTIAGED DOUGLAS-FIR STANDS IN COASTAL NORTHERN CALIFORNIA

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Abstract. We studied how forest management decisions affect branching of coastal Douglas-fir (*Pseudotsuga menziesii* var. *menziesii*) in coastal northern California because knot sizes can affect performance, grade, and value of structural lumber. We focused on branching in the second log which is located immediately above the butt log and constitutes an important part of a tree's wood volume and potential value. Branch diameters were measured on multiple Douglas-fir trees nested within 40 plots sampling even-aged and multiaged stands. We analyzed two tree-level branch size metrics that can be influential in log grading: (i) the basal diameter of the largest branch on the log, and (ii) the average diameter of the largest branch on each quadrant (termed BIX). Generalized linear mixed-effects regression analysis revealed that branches were smaller in multiaged stands than even-aged stands. Trees with larger branches also had larger DBH and crown width, and lower height:diameter ratio. Branch diameters were more sensitive to competition from their nearest neighboring trees than overall stand density or basal area of larger trees. Since neighboring trees exerted control over branch development, and if large branches are undesirable, managers may consider implementing more dispersed patterns of retention and limiting creation of edges.

Keywords: BIX; knot size; *Pseudotsuga menziesii*; tree branching; uneven-aged silviculture; wood quality.

1 INTRODUCTION

The decision to practice even-aged or multiaged forest management has the potential to affect the quantity and value of forest products and services into the future (O'Hara 2014). Multiaged stand structures are more complex than even-aged stands comprised of one evenly-spaced cohort of trees with approximately equal access to growing space (Oliver and Larson 1996). Under multiaged management, there is unequal access to growing space among individual trees developing in different environments (Peng 2000). Partial harvest creates openings in the canopy allowing the new cohort to establish (Ashton and Kelty 2018). This new cohort's tree crowns and branching will change in response to shade from older (taller) cohorts (Oliver and Larson 1996). Subsequent partial harvests alter the light environment for understory trees, reducing competition and allowing their stems and branches to respond to the changing conditions (Pretzsch & Rais 2016).

Forest managers may be interested in the size of tree branches for several reasons. Larger branches persist for longer on the tree stem before decaying, breaking, and falling to the ground (Oliver and Larson 1996). Trees with large lower branches are more likely to allow fire to climb into the tree crown which can result in active crown fires within forests in fire-prone regions (Wagner 1977). Trees with large branches yield sawn lumber with large knots which can impact the performance and value of wood products (Schniewind & Lyon 1973; Whiteside et al. 1977; Williams et al. 2000; Briggs et al. 2007). The size of the largest branches and knots in each log will determine structural log and lumber grades (Middleton & Munro 1989, cited in Lowell et al. 2014; Maguire et al. 1999; Mäkinen & Hein 2006; Xu 2002).

The relationship between tree branches and stand density has been well studied in even-aged stands (Pretzsch & Rais 2016). Of particular interest is how forest management affects branching and knot size in species used for structural applications such as coast Douglas-fir (*Pseudotsuga menziesii* var. *menziesii*) (Lowell et al. 2014). Key factors affecting branch and knot size are planting density (Grah 1961; Briggs et al. 2007) and the timing, frequency, and intensity of thinning (Weiskittel et al. 2007; Lowell et al. 2018). Maguire et al. (1991) linked models predicting Douglas-fir branching to tree attributes forecast by an individual-tree distance-independent growth and yield model. Using this system of equations, they found substantial differences in wood quality among long butt logs (12.2 m length) grown under different silvicultural prescriptions (Maguire et al. 1991). Stand density also affects stem allometry and crown ratio (Curtis & Reukema 1970; Wonn & O'Hara 2001; Berrill et al. 2012) which are variables likely correlated with branch size. Additional sources of variation in tree branching may relate to wood properties or crown morphology that are themselves variable phenomena challenging modelers to adopt innovative approaches (Yeatts 2012; Cieszewski et al. 2013).

The influence of multiaged stand density and structure is linked to stand growth and yield (e.g., Berrill & Boston 2019), but its influence on branching has not received as much attention as branching in even-aged stands (Pretzsch & Rais 2016). Kirk & Berrill (2016) studied branch growth in mixed multiaged stands in Mendocino County, California. They reported that the mid-tolerant Douglas-fir had a greater branch growth response to the treatments of partial conifer harvest and herbicide hardwood control than did the shade-tolerant coast redwood (*Sequoia sempervirens*). They also found that residual overstory conifer branches in harvested plots responded almost immediately with increased growth, but that this 'release' was short-lived. In contrast, conifer branches in herbicide-treated plots had more moderate response, and release was delayed giving more consistent branch growth throughout the two five-year periods after herbicide treatment of hardwoods growing among the conifers (Kirk & Berrill 2016). Sprugel (2002) compared branches of the shade-tolerant Pacific silver fir (*Abies amabilis*) between trees with crowns located in sun and shade. Trees with crowns receiving direct sunlight exhibited mortality of self-shaded lower branches, unlike trees growing in partial shade that retained their lower branches. The lower branches of shaded trees, such as those we might find in the understory of multiaged stands, continued to survive at low light levels where overstory tree branches had died (Sprugel 2002). Conversely, white pine (*Pinus strobus*), a species of intermediate shade tolerance, had lower crown ratio in the understory than in the overstory (O'Connell & Kelty 1994). Taken collectively, these findings suggest that the position of tree crowns within a stand should be considered when studying branching.

We studied how second-log branch diameters are influenced by silviculture, with a particular focus on differences between even-aged vs multiaged Douglas-fir stands of coastal northern California. The second log can represent a significant portion of the total stemwood volume, ranging from 23% in tall trees comprising six logs up to 42% of total volume in smaller trees making only two 5-meter logs (Mesavage and Girard 1946, cited in Husch et al. 1973). Therefore, the second log can have a major influence on gain/loss in value from lumber grade demotion from excessive knot size (Bell and Dilworth 2002; WWPA 2017). Furthermore, second-log branches can persist to later ages than first-log branches (Oliver and Larson 1996), and pruning of the second log is generally cost prohibitive due to its height above ground. Therefore it would be useful to identify how stand density and stand structure could be manipulated to control branch size. Our study objectives were to evaluate the relationship of various tree- and stand-level variables to branch size, and to compare branch structure across two contrasting stand types. We hypothesized that the largest branches on the second log in Douglas-fir would be smaller among understory trees in multiaged stands than among trees in even-aged stands. We also expected to find larger branches on Douglas-fir grown at lower stand densities. Lastly, we hypothesized that models predicting basal diameter of the largest second-log branches as a function of absolute or relative tree size would be significantly improved by adding variables representing stem slenderness or vigor in terms of crown ratio, but not topographic variables (aspect, slope, or upslope catchment flow accumulation).

2 METHODS

2.1 STUDY AREA

The L.W. Schatz Demonstration Tree Farm (LWSDTF) is a 146 ha property located 24 km east of the Pacific Ocean and the city of Eureka, Humboldt County, north coastal California (40.77,-123.87). Elevations at the LWSDTF range from 145 to 420 meters above sea level. The LWSDTF encompasses all aspects and the topography varies from almost flat to over 70% slope. The soils are classified as sandstone and mudstone that are well-drained gravelly clay loams, very gravelly loam, or loams forming on mountain slopes, and having an average depth of 2 m (Soil Survey Staff, 2017). The LWSDTF is characteristic of Douglas-fir forest sites along the California Coast Range, experiencing a Mediterranean climate and having been clearcut in the last century. The LWSDTF currently comprises a mosaic of stands of Douglas-fir of different ages and age-structures. Douglas-fir had regenerated naturally and was planted (and underplanted) on a small scale, haphazardly over several decades, throughout the property. This patchiness and heterogeneity was ideal for our study since we sought to study branching in even-aged and multiaged stand structures representing different stand conditions. Another important factor that this site provided was that no commercial or pre-commercial harvesting has occurred since the current stands initiated. If past harvesting had occurred, the current stand densities would not correlate with past conditions that may have influenced branching which could cause modeling problems.

2.2 DATA COLLECTION

Throughout the entire LWSDTF, Douglas-fir stands were delineated and coded as having either even-aged or multiaged structure. Within each of the multiaged stands, a single circular fixed-radius 0.04 ha sample plot was established at a random location. Next, an equal number of 0.04 ha sample plots were randomly located in nearby even-aged stands (Figure 1). Slope and aspect were recorded for each plot. The location of each tree >15 cm diameter at 1.37 m breast height (DBH) was mapped by recording distance and azimuth from plot center. Tree DBH, total height, and live crown base height (LCBH) were measured. LCBH was considered to be the height of the lowest living branches connected to the continuous crown. Isolated or unconnected living branches were ignored. Two or three "focal trees" nearest plot center were then selected for branch measurements. The largest branch was identified in each radial quadrant of the bottom half of the second log 4.88-7.32 m above ground. We measured live crown radius (LCr), branch azimuth, number of influential neighbor trees, distance to the most influential neighboring tree, and crown over-

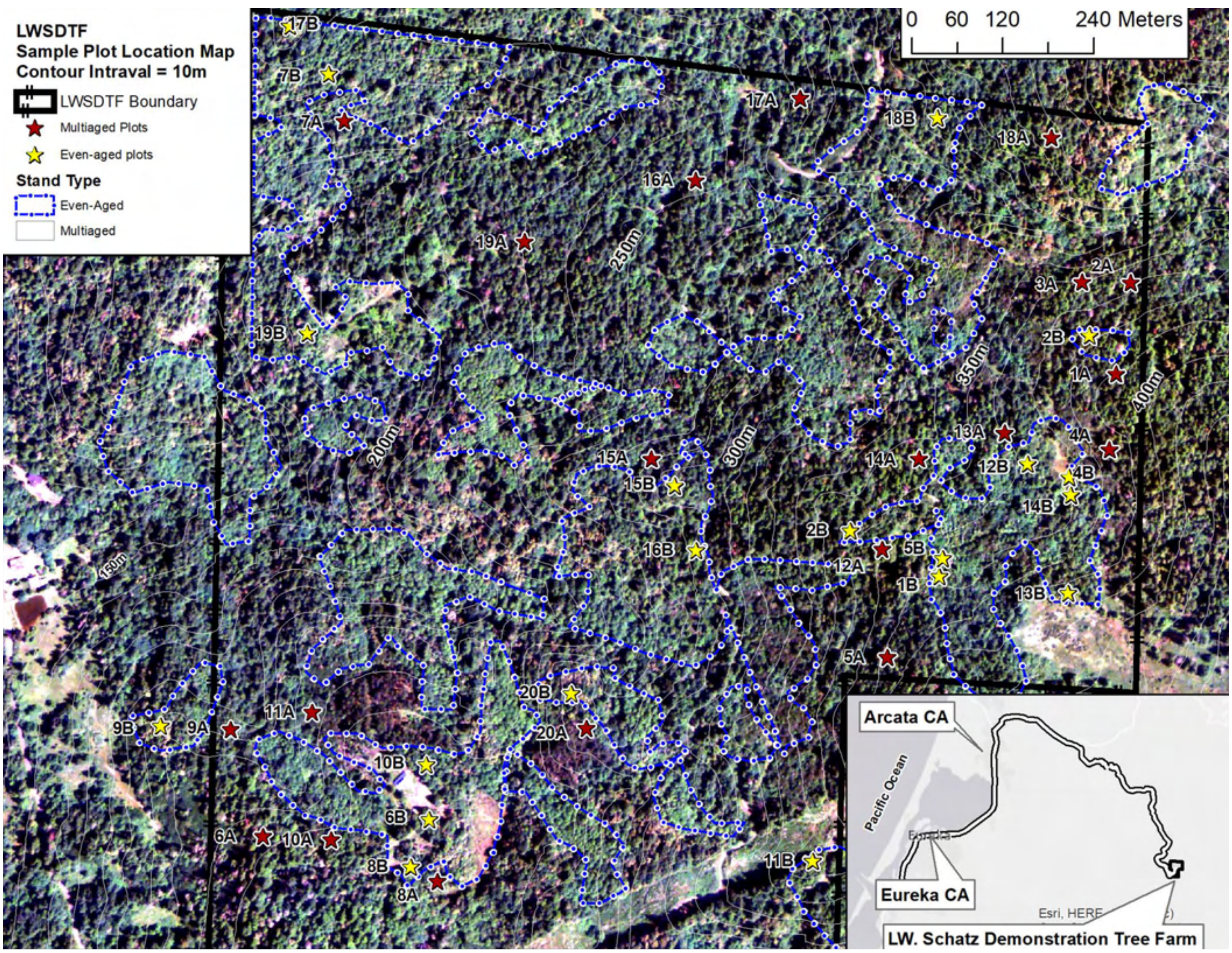

Figure 1: Distribution of branch diameter sample plots at LWSDTF in Humboldt County, California. Plot type A sampled multiaged and type B sampled even-aged Douglas-fir stands.

lap for the largest branch in each quadrant before removing it from the tree using a pole saw. The branch base diameter was measured adjacent to the branch collar at the thickest and narrowest points of its elliptical cross section using calipers. Focal trees were cored at breast height for age.

2.3 ANALYSIS

ArcMap was used to determine crown projection area of focal trees and neighboring trees (Supplemental File, Figure S1). Example visual representations of tree locations, sample branches, and crown area are provided in Supplemental File, Figure S2 & S3. Flow accumulation for each plot was derived from a 10 meter digital elevation model (DEM), giving a count of 10 x 10 m cells in the upslope catchment area. Aspect was cosine-transformed to a continuous 0–20 range where 0 was assumed to represent maximum exposure to the summer sun (SW, 225^o), 20 represented a NE aspect of 45^o, and 10 represented either SE or NW aspects.

Two types of second-log branch diameter models were created. The first type modeled the average diameter of the largest branch from each quadrant, known as BIX (Inglis & Cleland 1982, cited in Watt et al. 2000). The second model type predicted the maximum branch diameter (MaxB) in the bottom half of the second log (i.e., largest branch in all four quadrants). For both model types, generalized linear mixed-effects regression models were fitted to tree- and stand-level variables (Table 1). A random plot effect accounted for the hierarchical data structure with focal trees nested within plots (Faraway 2006). There were 91 records available for model fitting but some outlier observations detected using the Cook's distance and qq plots (Faraway 2005) were removed. R statistical software was used for regression analysis (R Development Core Team 2015).

Different variables were included in either the BIX or MaxB models. For BIX we averaged the largest branch diameters and their corresponding data for each quadrant of the tree. Alternatively, the MaxB model used specific variables recorded for the particular quadrant where the largest branch was measured. We calculated a competition index to represent relative size and distance of the most influential neighbor tree crown. This neighbor competition index (NCI) was the ratio of crown radius for the most influential neighbor tree to its distance from the focal tree. NCI was calculated for the specific quadrant associated with the largest second-log branch on the focal tree for MaxB analysis, or averaged for all four quadrants for BIX analysis. In an attempt to identify the best silvicultural treatment-related predictors of branch size, we fitted and compared models each containing one of the following five metrics representing stand density or neighbor competition: trees per ha, basal area per ha (BA), stand density index (SDI), basal area per ha of trees larger than the focal tree (BAL), or NCI.

Simpler predictive models for BIX and MaxB were also created for use with a variety of basic forest inventory data. The first inventory model used BA alone. The second model included DBH data that would be collected in fixed-area plots or point samples that include DBH class tallies. The DBH data were incorporated into the model directly as DBH, and also as a ratio of DBH relative to the plot average (DBH.p). The third inventory model also included a variable for tree height or the height:diameter ratio representing stem slenderness. Height data are not usually collected for all trees in a forest inventory, but we expected a better fit when using tree height or stem slenderness information to predict branch size.

Model selection based on AIC was used to determine the best combination of variables for each model (Anderson 2008). AIC for small sample sizes (AICc) was also calculated and reported for comparison. Using the same candidate predictor variables, we developed auxiliary regression models using generalized linear regression (GLM) to predict missing values of LCr (i.e., for neighboring trees adjacent to focal trees). GLM analysis was also used to compare Douglas-fir tree allometry between even-aged and multiaged plots by fitting regressions to tree height and LCBH data (Supplemental File, Table S1-S5).

3 RESULTS

A wide range of Douglas-fir focal tree sizes and stand conditions were sampled in 20 multiaged and 20 even-aged stands (Table 2). Within these 40 plots, a total of 91 focal trees and 364 branches were sampled. On average, focal trees had slightly larger DBH in even-aged plots but were slightly taller in multiaged plots. Stand-level and site variables were similar among plot types, except that stand density was higher on average, and more variable, for the multiaged plot type.

The average diameter of the largest branch in each quadrant of the second log (BIX) and the largest branch among all second-log quadrants (MaxB) were correlated with a similar suite of tree size and stand variables. Trees with high BIX and MaxB were relatively large (DBH.p) and had wide crowns (large crown radius, LCr) (Figure 2). The negative coefficients for competition variables (SDI, BAL, NCI) indicated that BIX was lower under more crowded conditions (Table 3). Regardless of whether SDI or BAL or NCI was included in the BIX model, the same set of predictor variables remained. The relative predictive power of these 'informative models'

Table 1: Candidate variables for branch diameter models.

Variable	Description	Type
Plot.type	Multiaged plot (A) or even-aged plot (B)	Categorical
Tpha	Number of trees per hectare	Continuous
BA	Basal area (m^2ha^{-1})	Continuous
SDI	Stand density index (metric)	Continuous
BAL	Basal area of trees larger (m^2ha^{-1})	Continuous
Slope	Slope of plot	Percentage
Aspect	Cosine transformed aspect (0=SW; 20=NE)	Range (0-20)
DBH	Diameter at breast height (cm)	Continuous
HT	Total height of tree (m)	Continuous
LCBH	Live crown base height (m)	Continuous
HDR	Height divided by DBH	Ratio
DBH.p	Target tree DBH divided by plot mean DBH	Ratio
Age	Age of tree at breast height (years)	Continuous
B.Azi	Azimuth of branch away from tree center	Range (0-20)
NCI	Neighboring tree crown coverage	Ratio
N.dist	Distance to the most influential neighbor	Continuous
Num.N	Number of influential neighbors	Continuous
LCr	Live crown radius (m)	Continuous

in terms of AIC and AICc ranked: NCI-model >BAL-model >SDI-model (Table 3).

A basic regression of BIX and BA in even-aged versus multiaged stands was abandoned because it did not make realistic predictions across the range of data collected. This suggested that tree size information was essential for predicting BIX. The simplest acceptable 'inventory model' included relative DBH (DBH.p), trees per hectare, and the binary categorical variable for even-aged or multiaged plot type. This 'DBH inventory model' was less effective at predicting BIX than inventory models including DBH and height information. The best-fitting 'DBH & HT inventory model' predicts BIX from DBH.p, trees per hectare, and tree height. Both of these inventory models indicated that trees with high BIX were relatively large, and were located in stands with fewer trees per hectare. Coefficients and fit statistics for the best-fitting BIX inventory models and the more complex informative models are listed in Table 3.

The same assortment of variables used in the BIX inventory models also predicted MaxB (Table 3). The MaxB model coefficients had the same sign (+/-) as BIX model coefficients, however the coefficient values were different since maximum branch diameter was always larger than the average of the four largest branches. Unlike the BIX analyses, we detected an age effect on MaxB where Douglas-fir of a given size had lower MaxB when they were slower grown (older). We also found that Douglas-fir with greater stem slenderness in terms of HDR had lower MaxB. Consistent with the BIX models, relatively large trees with wider crowns in terms of LCr had higher MaxB (Figure 2). Also consistent with the BIX models, the relative predictive power of MaxB models in terms of AIC and AICc ranked: NCI-model >BAL-model >SDI-model >DBH & HT-model >DBH-model (Table 3). Inventory model predictions of BIX and MaxB are shown in Figure 3.

4 DISCUSSION

Our findings help inform a shift in forest management focus from volume production to value production via greater recovery of more valuable log and lumber grades with smaller knots. Forest managers are advised that second-log branch diameters will generally be larger in even-aged stands. The exception was among the smallest trees in even-aged stands which had high HDR and small branches. Small trees in even-aged stands are not as vigorous as their neighbors, have smaller crowns, slender stems, and may be suppressed (Mohler et al. 1978). Conversely, a small tree growing in the understory of a managed multiaged stand should not be experiencing excessive competition if stand density is being adequately controlled (Long & Daniel 1990; O'Hara 2014). Where forest managers are converting even-aged stands to multiaged management, the understory cohort establishing under the residual overstory trees will have smaller branches than those on trees currently being harvested during the conversion process. If this difference translates into an increase in wood quality, it should enhance future value which may help offset the income

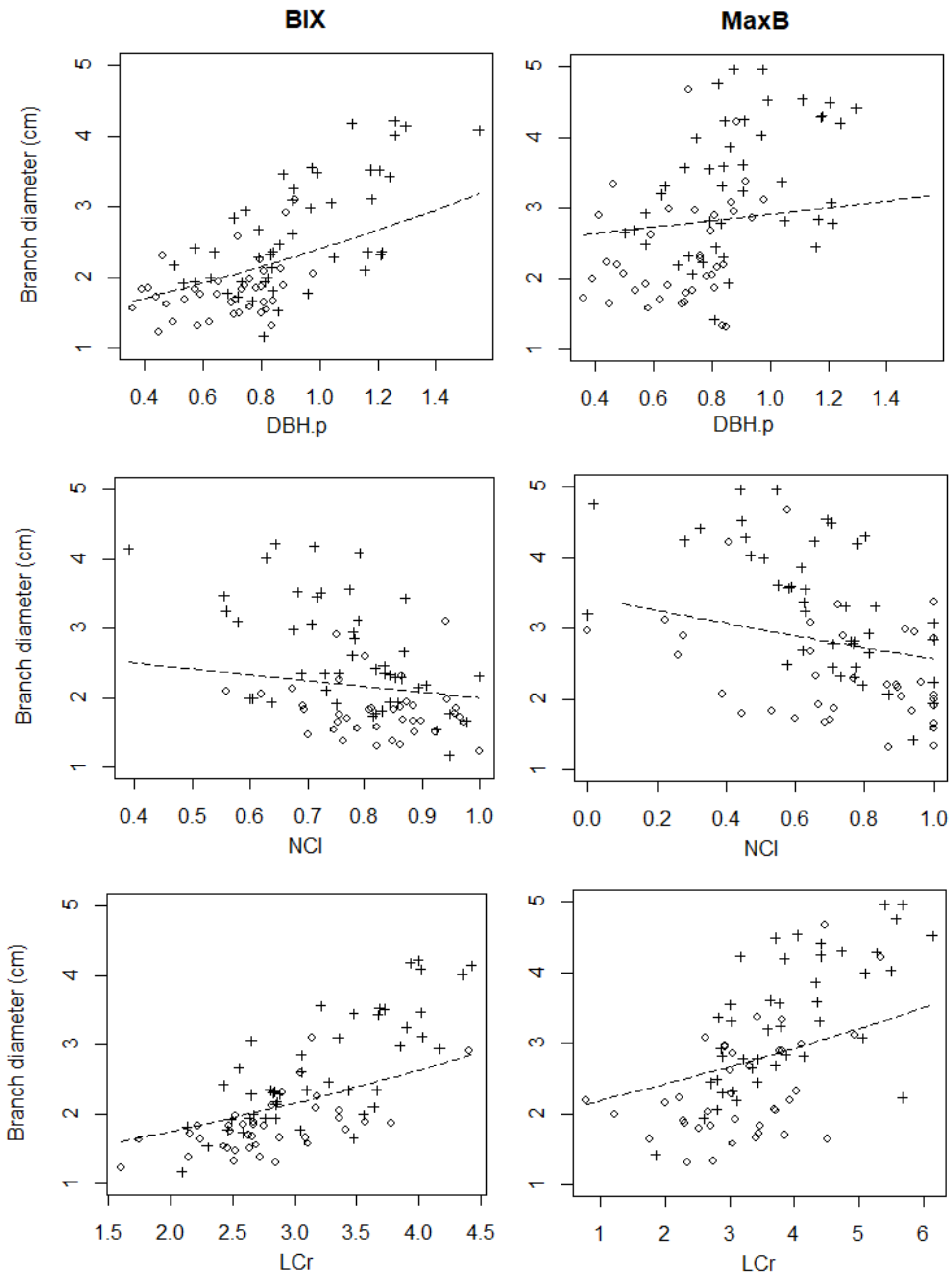

Figure 2: Douglas-fir branch diameter in terms of BIX (left) and MaxB (right) with predictions from the best-fitting model superimposed over actual data, where (o) denotes multiaged data and (+) denotes even-aged stand data, depicting the modeled effect of relative tree size (DBH.p; top), neighbor competition index (NCI; middle), and crown radius (LCr; bottom) with all other variables held constant at their mean value.

foregone by converting to multiaged management instead of clearcutting (Nyland 2003).

We found differences in tree allometry between even-aged and multiaged stands (Supplemental File, Table S1-S5). Douglas-fir HDR was greater (i.e., stem more slender) in the understory at LWSDTF, suggesting that these trees would be less windfirm (Wonn & O'Hara 2001). However, HDR may not be such a strong indicator of tree stability in multiaged stands as opposed to even-aged stands. Stability of trees in multiaged stands

Table 2: Summary table of Douglas-fir focal tree and branch level variables, and stand-level variables for multiaged (MA) and even-aged (EA) plot types at LWSDTF Humboldt County, California. BAL = Basal area of trees larger than focal tree (m^2ha^{-1}). Flow accumulation = number of ten meter cells contributing water to the plot. Neighbor tree crown area is plot sum (m^2). BIX = average diameter of largest branch in each quadrant of second log; MaxB = diameter of largest branch among four quadrants of the second log.

Variable	Mean		S.D.		Min		Max	
Plot Type:	MA	EA	MA	EA	MA	EA	MA	EA
Focal tree attributes								
DBH (cm)	24.9	27.9	5.5	6.5	15.2	15.5	36.1	42.9
Tree height (m)	25	21	4	3	17	16	37	29
Crown ratio	45%	58%	15%	16%	21%	21%	95%	88%
Mean neighbor dist. (m)	4.3	4.3	1.2	1.4	1.8	1.7	6.6	7.5
LCr (m)	2.8	3.2	0.9	1.1	2.8	3.2	5.5	6.3
Breast-height age (years)	43.0	34.0	3.6	3.9	52.0	40.0	70.0	49.0
BIX (cm)	1.9	2.7	0.5	0.8	1.1	1.2	3.2	4.2
MaxB (cm)	2.4	3.5	0.8	1.2	1.3	1.4	4.7	6.5
Focal tree crown area (m^2)	45.8	67.3	11.8	19.7	26.5	40.6	67.0	122.5
BAL (m^2ha^{-1})	62.3	34.8	23.8	15.5	29.5	2.8	115.8	66.0
Neighbor crown area above	344.3	220.4	204.6	126.3	91.2	77.9	848.5	564.9
Neighbor crown area below	98.5	93.3	83.8	94.9	0.0	0.0	286.2	385.9
Stand-level variables								
SDI (metric)	1051.0	860.0	274.2	209.3	647.0	436.0	1605.0	1109.0
BA (m^2ha^{-1})	69.0	49.0	22.2	13.0	40.0	23.0	116.0	67.0
Tpha (trees ha^{-1})	514.0	590.0	142.7	164.1	275.0	350.0	800.0	900.0
Average DBH (cm)	37.0	30.9	19.7	10.8	15.2	15.2	163.3	83.1
Average tree height (m)	26.0	21.0	7.5	4.7	8.0	4.0	57.0	37.0
Average crown ratio	53%	60%	14%	14%	19%	19%	100%	92%
Flow accumulation	21.1	20.5	37.6	60.4	0.0	0.0	166.0	275.0
Slope (%)	25.0	29.0	10.6	15.1	8.0	8.0	45.0	64.0
Aspect (0 – 20)	9.0	8.0	6.2	7.4	0.0	0.0	20.0	20.0

may be enhanced due to a variety of factors including slower growth while in the understory, followed by progressively greater exposure after each partial harvest. Schelhaas (2008) found that Douglas-fir were relatively more stable under the individual-tree selection silvicultural system when partial harvesting removed the most slender trees and maintained low densities, and less stable in various even-aged stands where management led to higher HDR. Differential exposure to sunlight and shade related to differences in stand structure, species composition, or topography may affect HDR (e.g., Milios et al. 2018). We found Douglas-fir to be taller for a given DBH on north-facing slopes than on south-facing slopes. Consistent with our Douglas-fir analyses, ponderosa pine (*P. ponderosa*) also alters its growth and HDR according to aspect (Verbyla & Fisher 1989). However, topography did not have a significant influence on BIX or MaxB in our regression analysis. Live crown base height (LCBH) is expected to exhibit variation according to stand density (Temesgen et al. 2005), and according to crown position within the stand as it relates to the amount of shade experienced by the tree crown (Sprugel 2002). We found that Douglas-fir LCBH was lower in multiaged plots, after accounting for the difference in HDR. From this finding we infer that Douglas-fir in the understory with the same HDR as a tree within an even-aged stand may have slower crown rise rates, consistent with observations of lower branches surviving in low light for more shade tolerant species grown in shade as opposed to direct light (Sprugel 2002). The absence of relationship between Douglas-fir crown radius and stand density is also consistent with other studies (Kantola & Mäkelä 2004; Mäkinen & Hein 2006).

Table 3: Douglas-fir BIX and MaxB branch model coefficients for fixed effects (s.e. as percent of coefficient in parentheses), and random effects variance components, for "inventory" and "informative" models. Categorical plot type variable: A=multiaged; B=even-aged. Model AICc and AIC indicate relative predictive power, where smaller value is better.

Fixed/random effects	DBH Inventory		DBH&HT Inventory		Informative SDI		Informative BAL		Informative NCI	
BIX models										
Intercept	1.0940	(5%)	1.2884	(5%)	1.0360	(7%)	1.0418	(7%)	1.1650	(8%)
Plot type B	0.0963	(27%)	—	—	—	—	—	—	—	—
Tree height (m)	—	—	-0.0109	(20%)	-0.0086	(24%)	-0.0085	(25%)	-0.0084	(24%)
LCr (m)	—	—	—	—	0.1001	(18%)	0.1020	(18%)	0.0870	(22%)
Tpha (trees ha^{-1})	-0.0003	(32%)	-0.0002	(33%)	—	—	—	—	—	—
SDI (metric)	—	—	—	—	0.0000	(140%)	—	—	—	—
NCI	—	—	—	—	—	—	—	—	-0.1633	(46%)
BAL (m^2ha^{-1})	—	—	—	—	—	—	-492.0000	(134%)	—	—
DBH.p	0.3543	(13%)	0.4772	(9%)	0.2332	(23%)	0.2072	(34%)	0.2383	(22%)
Random: Plot	0.0030		0.0029		0.0024		0.0024		0.0025	
Residual	0.0055		0.0047		0.0038		0.0038		0.0035	
AICc	-126.3		-130.5		-138.5		-144.0		-157.4	
AIC	-127.4		-131.6		-140.0		-145.4		-158.9	
MaxB models										
Intercept	1.2436	(6%)	1.5420	(6%)	1.6940	(8%)	1.7003	(8%)	1.7288	(7%)
Plot type B	0.1293	(27%)	—	—	—	—	—	—	—	—
Tree height (m)	—	—	-0.0170	(18%)	—	—	—	—	—	—
LCr (m)	—	—	—	—	0.0594	(21%)	0.0585	(21%)	0.0437	(28%)
Age (years)	—	—	—	—	-0.0055	(24%)	-0.0056	(24%)	-0.0052	(24%)
Tpha (trees ha^{-1})	-0.0003	(34%)	-0.0003	(34%)	—	—	—	—	—	—
SDI (metric)	—	—	—	—	0.0000	(125%)	—	—	—	—
NCI	—	—	—	—	—	—	—	—	-0.1405	(32%)
BAL (m^2ha^{-1})	—	—	—	—	—	—	-0.0004	(191%)	—	—
HDR	—	—	—	—	-0.2970	(25%)	-0.3033	(25%)	-0.2644	(27%)
DBH.p	0.3446	(19%)	0.5224	(11%)	0.0246	(255%)	0.0102	(782%)	0.0750	(79%)
Random: Plot	0.0045		0.0039		0.0003		0.0004		0.0011	
Residual	0.0112		0.0093		0.0085		0.0084		0.0069	
AICc	-72.8		-82.1		-93.7		-98.8		-115.8	
AIC	-73.9		-83.2		-95.7		-100.8		-117.7	

Multiaged stand management effects on branch size have previously been considered (O'Connell & Kelty 1994; Kirk & Berrill 2016). However our study is novel due to the direct comparison and quantification of second-log branch diameters in multiaged vs. even-aged stands. The limitation of our study was being restricted to one geographic location. We recommend sampling branches across a variety of locations to validate the finding that Douglas-fir second-log branches were generally smaller in multiaged stands. We also recommend evaluating a range of branch size variables such as BIX and MaxB that are known to correlate with sawn lumber recovery (Todoroki et al. 2001), and recommend making plans to undertake sawmill studies when monitored trees are eventually harvested.

Silvicultural decisions can influence Douglas-fir BIX and MaxB. The negative correlation of smaller branch diameter with increasing stand density has been well documented (Newton et al. 2012; Pretzsch & Rais 2016). Douglas-fir MaxB was negatively influenced by SDI at the LWSDTF; however the local competition factor, NCI was a better predictor of MaxB. This suggested that Douglas-fir at LWSDTF may have higher morphological plasticity and lower epinastic control than expected because its branches will grow more in some directions than others to exploit adjacent openings (Oliver & Larson 1996; Pretzsch & Rais 2016). Therefore we expect spatial patterns of tree retention after thinning or partial harvesting will have greater influence on future branch size than overall post-treatment SDI. The management implications of this finding are profound; larger branches

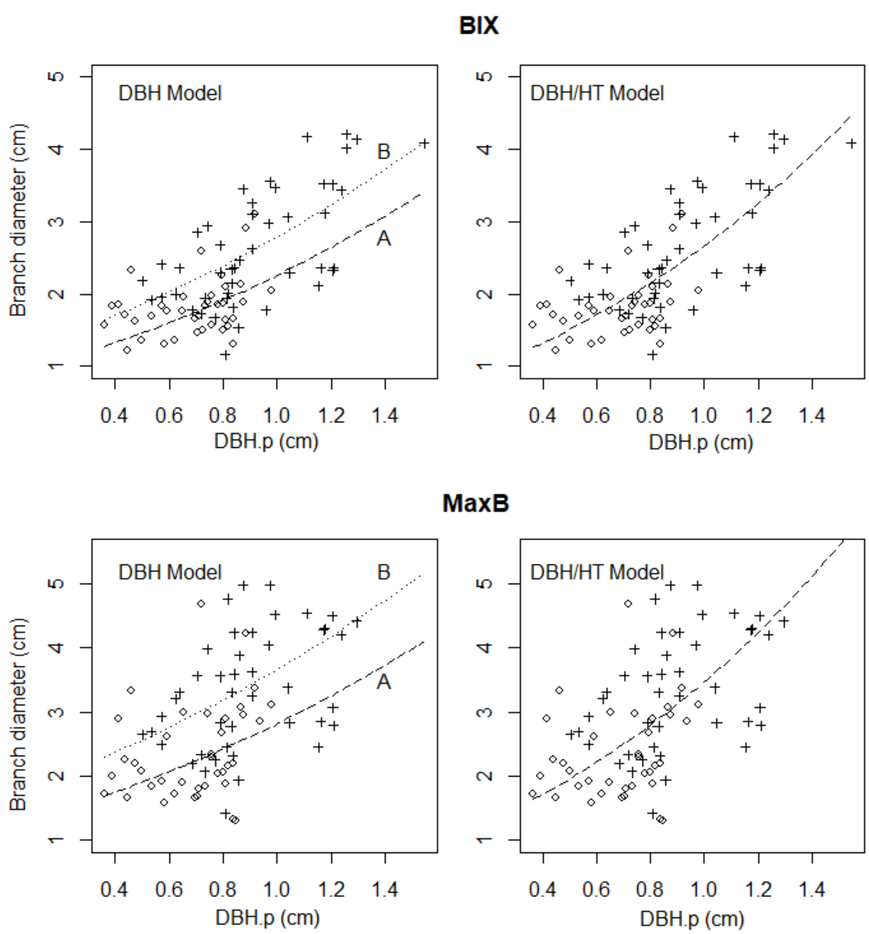

Figure 3: Branch diameter relationship to relative tree size (DBH.p) for Douglas-fir BIX (top) and MaxB (bottom) depicted by predictions from two 'inventory models': the DBH model, and DBH & Height model for multiaged (A) and even-aged (B) plot types, superimposed over actual data, where (o) denotes multiaged data and (+) denotes even-aged stand data.

constitute ladder fuels which can lead to crown fires (Wagner 1977). Large branches can also negatively impact structural lumber performance (Schniewind & Lyon 1973) and if large enough, reduce the lumber grade to a less valuable product (Bell and Dilworth 2002; WWPA 2017). Removal of branches by pruning of second logs is prohibitively expensive and seldom practiced, and pruning of Douglas-fir to remove large branches creates large wounds with long occlusion time (Petruncio et al. 1997; Lowell et al. 2014). Other options for second-log branch size control include selective tree breeding (Burdon and Moore 2018), but not necessarily for Douglas-fir where silviculture has more influence than genetics on knot size (Vikram et al. 2011). The simplest silvicultural strategy could be to delay thinning or partial harvesting until the live crown base has risen above the second log. Given that relative tree size (DBH.p) was a better predictor of branching than DBH, we expect thinning-from-below to remove smaller trees will leave larger-branched trees remaining in the stand. Therefore it may be advisable to adopt alternative thinning methods such as crown thinning to remove relatively large trees with excessively large branches (Ashton & Kelty 2018). Another practical solution may be to design stand structures that limit branch size development. Branch size control from neighbors is absent along the edges of openings or clumps (Oliver and Larson 1996). Edges are created adjacent to roads and landings and after clearcutting or implementing group selection, some shelterwood variants, or aggregated variable retention silviculture. To mitigate problems of excessive branch size we recommend maintaining large stand areas so that edges and openings are minimized, and either providing partial shade from larger trees to restrict second-log branch size in multiaged stands, or maintaining uniformity of tree spacing within even-aged stands, so that development of second-log branches is restricted by adjacent trees.

Forest managers may want to use our models to predict branch diameter, but not have access or means to obtain the crown radius or NCI data used to parameterize the complex informative models we presented. To provide flexibility we created progressively simpler models that included variables derived from forest inventory data. Among these ‘inventory models’, branch size was best predicted by models including tree height or HDR. Height measurements are not always available for all trees in forest inventories. Therefore the DBH-based models may also be useful for forest managers seeking indicative estimates of branch size to help anticipate outcomes of different silvicultural treatment options. Overall, the suite of predictive models developed in this study have enhanced our understanding of tree and branch development in even-aged and multiaged stands, allowing for informed forest management decisions to reduce branch sizes for fire risk reduction and to reduce knot-related defects associated with branch size.

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