Eccentricity and Fluting in Young–Growth Western Hemlock in Oregon

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ABSTRACT: *Stem irregularities can influence estimates of tree and stand attributes, efficiency of manufacturing processes, and quality of wood products. Eccentricity and fluting were characterized in young, managed western hemlock stands in the Oregon Coast Range. Sixty-one trees were selected from pure western hemlock stands across a range of age, site, and densities. The trees were felled and disks were removed from breast height, base of live crown, and various percentage-of-height locations along the bole. Indices of out-of roundness (OOR), pith-off-center (POC), and fluting severity (fluting index) were computed, flutes were counted, and depth of deepest flute was measured on each disk. These variables were related to relative tree height, tree diameter, and several stand- and tree-level attributes. The lower portions of stems tended to be more out-of-round and have a higher degree of off-centered piths than upper stem heights. Basal and breast-height disks had a higher number of flutes, deeper flutes, and higher fluting severity compared to disks from upper stem positions. Tree size (diameter at 4.5 ft) was only weakly correlated with OOR and uncorrelated with POC, but strongly correlated with more flutes, deeper flutes, and higher fluting severity. OOR and POC were not significantly correlated with any other tree or stand attributes. The fluting variables were positively correlated with stand age and overall tree growth rate and negatively correlated with trees/ac. Thus, silvicultural practices that result in more rapid growth, wider spacing, and longer rotations are likely to result in more extensive fluting but will have little or no effect on stem eccentricity. West. J. Appl. For.18(4):221–228.*

Key Words: *Tsuga heterophylla*, stem eccentricity, fluting, stem irregularities.

Tree boles often exhibit some degree of eccentricity or noncircular shape in cross-section and occasionally feature some amount of fluting. Stem deformities can have an effect on the accuracy of predicting tree and stand attributes and also on manufacturing processes and the nature and quality of wood products. Western hemlock (*Tsuga heterophylla*), a commercially important tree species of the Pacific Northwest, is prone to having eccentric stems or fluting. Despite the dominance of Douglas-fir (*Pseudotsuga menziesii*) in the Pacific Northwest, significant acreages of western hemlock stands have been established, and the importance of young-growth hemlock in managed forest ecosystems and in the region's economy is expected to increase. This outlook seems particularly likely in the Coast Range of Oregon and Washington where Swiss needle cast caused by *Phaeocryptopus gaeumannii* is decreasing productivity in Douglas-fir plantations (Maguire et al. 2002).

In most applications in forest mensuration, the geometry of a cross-section at any one point along a tree stem is generally assumed to be circular when diameter is measured. Any noncircularity in the cross-section may therefore introduce varying amounts of error in estimates of individual tree basal area, growth, and subsequent volume estimates, as well as several indices of stand density. For noncircular stems, girth (tape wrap) measurements tend to lead to positive biases (overestimation), and caliper and increment core borings can lead to positive or negative biases when calculating total basal area (Matern 1956, Biging and Wensel 1988, Gregoire et al. 1989), basal area growth (Matern 1962, Iles 1974), and sapwood cross-sectional area (Maguire et al. 2002). In addition, out-of-roundness in stems can lead to small biases in stand volume estimates and large biases in individual tree volumes (Williamson 1975).

Eccentricity can include noncircularity, off-centered pith, or both in the cross-section. Studies have evaluated such

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characteristics in various species, and some consistencies are apparent. Stump and breast-height cross-sections were found to be more eccentric than upper stem positions in Douglas-fir trees (Reukema 1971, Williamson 1975). One study found a positive relationship between eccentricity and tree diameter at breast height (dbh) in Douglas-fir (Williamson 1975). Kellogg and Barber (1981), however, did not find a significant relationship between eccentricity and dbh for western hemlock in British Columbia.

Although less studied, highly fluted stems can have a profound affect on volume predictions and recoverable tree volume. Flutes are defined as longitudinal depressions in the bole resulting from inconsistent radial growth. They originate between pronounced buttresses at the base up to any height in the tree (Day 1964). Fluting can lead to the formation of bark seams that are considered a defect in poles and cause difficulties with peeling and sawing. Debarking fluted logs may also be problematic and costly (Harris and Farr 1974, DeBell and Gartner 1997).

Fluting has been found to exhibit many of the same patterns as eccentricity. Two studies found that the majority of fluting was in the lower portion of the bole in both western hemlock (Julin et al. 1993a) and western redcedar (*Thuja occidentalis*) (DeBell and Gartner 1997). It has also been reported that frequency of flutes and depth of flutes increase with tree diameter and with wider spacing in stands (Oliver et al. 1988, Julin et al. 1993a, DeBell and Gartner 1997). In addition, several stand and tree level characteristics including site, genetics, crown class, and tree age influence fluting in western hemlock in southeast Alaska (Julin et al. 1993b).

There has been little research on stem deformities in young, managed stands of western hemlock, particularly in the Oregon Coast Range. The objectives here were to characterize eccentricity and fluting in young-growth western hemlock growing throughout the northern Coast Range of Oregon with respect to tree size, relative tree height, and several stand and tree level attributes.

Methods

Study Area, Field Procedures, and Data

Sixty-one trees were sampled for this project; they represent a subsample of trees felled for a larger research project on industrial forestland in the northern Coast Range of Oregon. The project area extended from Tillamook to the Columbia River and reached inland to include the eastern foothills of the Coast Range mountains. Trees were selected from a list of trees within plots established in pure western hemlock stands that represented a matrix of three stand age, site, and density classes. The age classes of stands in the matrix were (1) under 30 yr, (2) 30–45 yr, and (3) 45–60 yr and both site and density were classified as low, medium, and high.

Twenty-four of the 61 trees were selected from plots in the older age classes from high and low site classes but with similar stand density. The oldest age was chosen since it provided the widest range of cambium ages to characterize. The high density class was selected because it represented fully stocked stands nearing a typical industrial rotation. The sampling scheme consisted of felling four trees on each of six plots (three plots each from high and low site classes). Trees on the plots from each of the selected stands were grouped into two classes of dominants and codominants in one class and smaller intermediates in another. In each stand, three trees were randomly selected from the dominant and codominant trees and one from the intermediate trees for felling. Cross-sectional disks were collected at five points in each tree, representing the following percentages of total height: 2% (disk_2), 10% (disk_10), 30% (disk_30), 50% (disk_50), and 70% (disk_70). In addition, disks were taken from breast height (disk_bh) and at base of live crown (disk_blc) (height where live braches are present around _ of the bole). This sampling gave a total of 168 samples—7 disks from each of 24 trees.

An additional 37 trees were chosen for assessment of stem form and wood properties such that they represented the full range of diameter and crown ratio classes. These trees were studied to provide additional information on stem characteristics at two critical locations along the bole, breast height and base of live crown. This sample plus the 24 multidisk samples resulted in 61 total trees from which disks at breast height (disk_bh) and base of live crown (disk_blc) were taken. However, some disks were broken during bucking or transport and were not measurable, reducing the total sample (Table 1). Table 2 summarizes stand- and tree-level characteristics of the sample trees. Trees/ac and site index were based on inventory data. Site indices were computed using curves prepared by Flewelling (Bonnor et al. 1995) for western hemlock.

Lab Procedures

Transport and Storage

The disks were transported from the field to the OSU Forest Research Lab within 4 days after cutting and stored at 5°C to curtail drying and fungal growth. After all the samples were collected and stored, a small cut was made from bark to pith on each disk to prevent radial checking when dried. The disks were then placed on pallets and air-dried using fans to prevent molding.

Eccentricity Measurements

Eccentricity was described in these trees using two indices; one for the extent to which the stem is not circular in cross-section (out-of-roundness), and the other for the extent to which the pith is not in the center

Table 1. Number of samples for each disk height. Note that some disks were broken and not measurable, thus not equaling the original sample total.

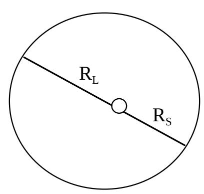
Disk	24 multidisk trees	37 additional trees	Total sample no.
2	20	—	20
10	24	—	24
30	23	—	23
50	22	—	22
70	24	—	24
bh	22	34	56
blc	23	36	59
Total:	158	70	228

Table 2. Means and standard deviations of attributes for 24 multidisk trees and 37 additional trees.

	24 multidisk trees from 6 stands				37 additional trees from 17 stands			
	Mean	SD	Min	Max	Mean	SD	Min	Max
Dbh (in.)	16.71	6.85	7.17	33.23	13.29	6.42	5.35	30.20
Total height (ft)	98.64	19.38	62.66	130.58	76.30	26.52	37.40	131.56
Crown ratio	0.46	0.09	0.29	0.66	0.54	0.20	0.25	0.98
Tree age	52.0	17.04	30	112	36.33	12.84	10	62
Site index	107.7	4.8	101.1	114.4	114.4	12.0	101.4	137.3
Trees/ac	266.0	114.9	161.4	482.3	527.6	372.4	161.4	1,158.4

(pith-off-centered). In order to calculate an index of out-of-roundness (OOR, Williamson 1975) two diameters were measured. First, the maximum cross-sectional diameter (D_{max}), not necessarily passing through the pith, was marked and measured. Then, a "minimum" diameter (D_{min}) was measured, defined as the cross-sectional distance perpendicular to the maximum diameter. OOR was calculated as follows: OOR = $(D_{max} - D_{min})/D_{max}$. Higher values of OOR are associated with more eccentric stems, while a circular stem would have a value of zero.

The degree to which the pith was off center of cross-sectional disks was described with a pith-off-center index (POC). A cross-sectional line was drawn such that its length (outside bark) was equal to the average cross-sectional diameter (determined by tape wrap) and its position contained the pith and the shortest (R_S) and longest radii (R_L) obtainable with the two prior constraints. The formula (see example diagram) for this index was computed as follows:



$$POC = (R_{AVG} - R_S) / R_{AVG}$$

where

R_S = short radius

R_L = long radius

R_{AVG} = average sample radius: $(R_S + R_L)/2$

Higher POC values indicate the pith is more off-centered.

Fluting Measurements

Fluting was evaluated using three variables: the number of flutes (*Flutes*), the depth of the deepest flute (*Depth*), and fluting index (*FI*). To qualify as a flute, a criterion was established based on tree size. A flute was defined as any depression between adjacent ridges, the depth of which was equivalent to at least 5% of mean radius of the disk. Mean radius was defined as half of the average diameter measured by tape wrap, and number and depth of flutes were determined by measuring the perpendicular distance from the wrapped tape to the deepest point of the flute.

The fluting index of DeBell and Gartner (1997) was used. The disks were measured for circumference using a steel tape (C_t), which was held tight such that it spanned flutes if any existed. An "actual" circumference (C_a) was determined by wrapping masking tape around the entire disk adjacent to the bark, leaving no spaces between the tape and the bark; the masking tape was then removed and its length measured. Fluting index was computed as:

$$FI = [(C_a / C_t) - 1] * 1000$$

Higher values of *FI* represented more severe fluting.

Analyses

Patterns with Height

Change in eccentricity and fluting with tree height was evaluated both graphically and with statistical models. Means and standard errors were graphed for the seven disk heights for out-of-roundness, pith-off-center, number of flutes, depth of deepest flute, and fluting index.

The seven disk heights were compared statistically with multivariate analysis of variance (MANOVA). We recognized that a lack of independence exists for the different heights within a tree, so the variables were graphed across disk height to confirm the conclusions of the analysis of variance. The 24 multidisk tree sample was used for the percent of height disks (Table 3). The 61 tree sample was used for the breast-height and base of live crown disks Table 3). Separation of means was evaluated using Fisher's protected least-square difference for unequal sample sizes (Fisher 1966). Means were considered significantly different at the $\alpha = 0.05$ level. Each of the fluting variables (number of flutes, depth of deepest flute, and fluting index) had skewed distributions, having several small or zero values and a few larger values. Several transformations were attempted, none of which could normalize the distribution or stabilize the variance. All statistical models were therefore run using untransformed data since these tests tend to be robust to departures from normality and nonconstant variance (Scheffe 1959).

Table 3. Basic statistics of disk height (ft) from the base of the tree.

Disk	*N*	Mean	SD	Min	Max
2	20	1.96	0.37	1.3	2.5
bh	56	4.50	0	4.5	4.5
10	24	9.89	1.91	6.3	13.0
30	23	29.30	5.69	18.8	39.1
blc	59	43.58	20.91	2.9	85.0
50	22	48.98	9.40	31.3	63.3
70	24	69.15	13.56	43.9	91.4

Effect of Tree Size

Regression models were developed to evaluate how changes in tree size affect eccentricity and fluting. Dbh was the explanatory variable representing tree size. The 61-tree sample using the breast height (disk_bh) disks for each eccentricity and fluting variable were used as the response variables. Simple linear regression models were fit separately for OOR, POC, and number of flutes, since the general relationship was linear between each response and dbh. Quadratic regression models were fit for depth of deepest flute and fluting index because of their curvilinear relationship to dbh.

Correlation with Other Tree and Stand Attributes

The linear association among trees/ac, site index, tree growth rate, tree age, and crown ratio, and the various eccentricity and fluting variables was investigated using correlation analysis on the breast-height disks. Stand-level variables (trees/ac, site index) were known for each stand from inventory plot data. One growth rate variable was periodic annual increment (PAI), calculated as the average annual radial growth rate during the last 10-yr period. The other growth rate variable was mean annual increment (MAI), calculated as the average annual radial growth rate over all years. Crown ratio was crown length divided by total height.

Results

Patterns with Height

Eccentricity

The lower portion of the bole, from disk_10 downward, was more out-of-round than higher portions of the bole (Figure 1a). OOR leveled off between 10 and 30% of total height. From disk_30 upward to disk_70, out-of- roundness was relatively constant. The model results agreed with those observations. Disk_2 was significantly different from all the disks above disk_10 (able 4). Disk_bh and disk_10 were significantly different from disk_30 and disk_blc but were not significantly different from disk_50 and disk_70.

The degree to which the pith was off center (POC) followed a similar pattern to out-of-roundness (Figure 1b). The lower disks (disk_2, disk_bh, and disk_10) tended to have higher mean POC values than did the upper disks, while POC remained relatively constant in the upper two-thirds of the bole. Again, the trends observed in the figure were backed by the model results. Disk_2 and disk_bh were significantly different from all disks above disk_10 (Table 4). Disk_10 was significantly different from disk_blc but not significantly different from any other disks.

Fluting

Disk_2 had the highest mean number of flutes and a high degree of variability (Figure 1c). The mean number flutes decreased markedly from disk_2 to disk_30 and remained at a low and constant level until disk_50. There were no flutes at disk_70. Statistically, disk_2 was significantly different from all other disks as was disk_bh (Table 4). There was no significant difference among disk_10, disk_30, disk_blc, disk_50, and disk_70.

Depth of deepest flute followed a similar pattern to number of flutes, with the highest values at the tree base and decreasing rapidly up the bole (Figures 1d). Disk_2 was significantly different from all other disks (Table 4). Disk_bh was significantly different from disk_30, disk_blc, disk_50, and disk_70. There was no significant difference among disk_10, disk_30, disk_blc, disk_50, and disk_70.

By a considerable amount, disk_2 had the highest mean fluting index (Figure 1e) and was significantly different from all other disks (Table 4). There was no significant difference among disk_bh, disk_10, disk_30, disk_blc, and disk_50, but disk_bh had a significantly higher fluting index than disk_70.

Effect of Tree Size

Eccentricity

Dbh was linearly related to out-of roundness (*P*-value = 0.0326), but only a small portion of the overall variation was explained by the model (R^2 = 0.0803). This relationship appears to have been influenced by the four samples above 25 in. dbh, which varied considerably in OOR (Figure 2a). Without these observations, the regression slope parameter for OOR was insignificant. Dbh had no linear relation to POC (*P*-value = 0.2190), and the variability of POC was extremely high for both small and large trees (R^2 = 0.0278) (Figure 2b).

Fluting

Number of flutes had a positive linear relationship with dbh (*P*-value = 0.0001) and had a moderately high coefficient of determination (R^2 = 0.4861) (Figure 2c). The polynomial regression models were significant for depth of deepest flute (*P*-value = 0.0001) and fluting index (*P*-value = 0.0001). The model for depth of deepest flute explained a large proportion of the variation (R^2 = 0.7203) (Figure 2d). Fluting index also had a relatively high coefficient of determination (R^2 = 0.6518) (Figure 2e).

Table 4. Results of MANOVA comparing disk heights for eccentricity and fluting variables. Fisher's protected lsd (FPLSD) was used for separation of means (significant differences occurred at α = 0.05). Means with the same letter are not significantly different. Note the number of observations per disk as follows: disk_2 = 20, disk_bh = 56, disk_10 = 24, disk_30 = 23, disk_blc = 59, disk_50 = 22, disk_70 = 24.

	OOR		POC		Flutes		Depth		Fluting Index	
Disk	lsmeans	FPLSD	lsmeans	FPLSD	lsmeans	FPLSD	lsmeans	FPLSD	lsmeans	FPLSD
2	0.1090	a	0.1708	a	2.286	a	1.0952	a	25.973	a
bh	0.0883	ab	0.1493	a	1.571	b	0.5381	b	8.039	b
10	0.0932	ab	0.1377	ab	0.625	c	0.2750	bc	5.184	bc
30	0.0629	c	0.0990	bc	0.174	c	0.0435	c	1.149	bc
blc	0.0650	c	0.0897	c	0.263	c	0.0781	c	2.768	bc
50	0.0690	bc	0.1034	bc	0.227	c	0.0409	c	1.274	bc
70	0.0707	bc	0.0998	bc	0	c	0	c	0	c

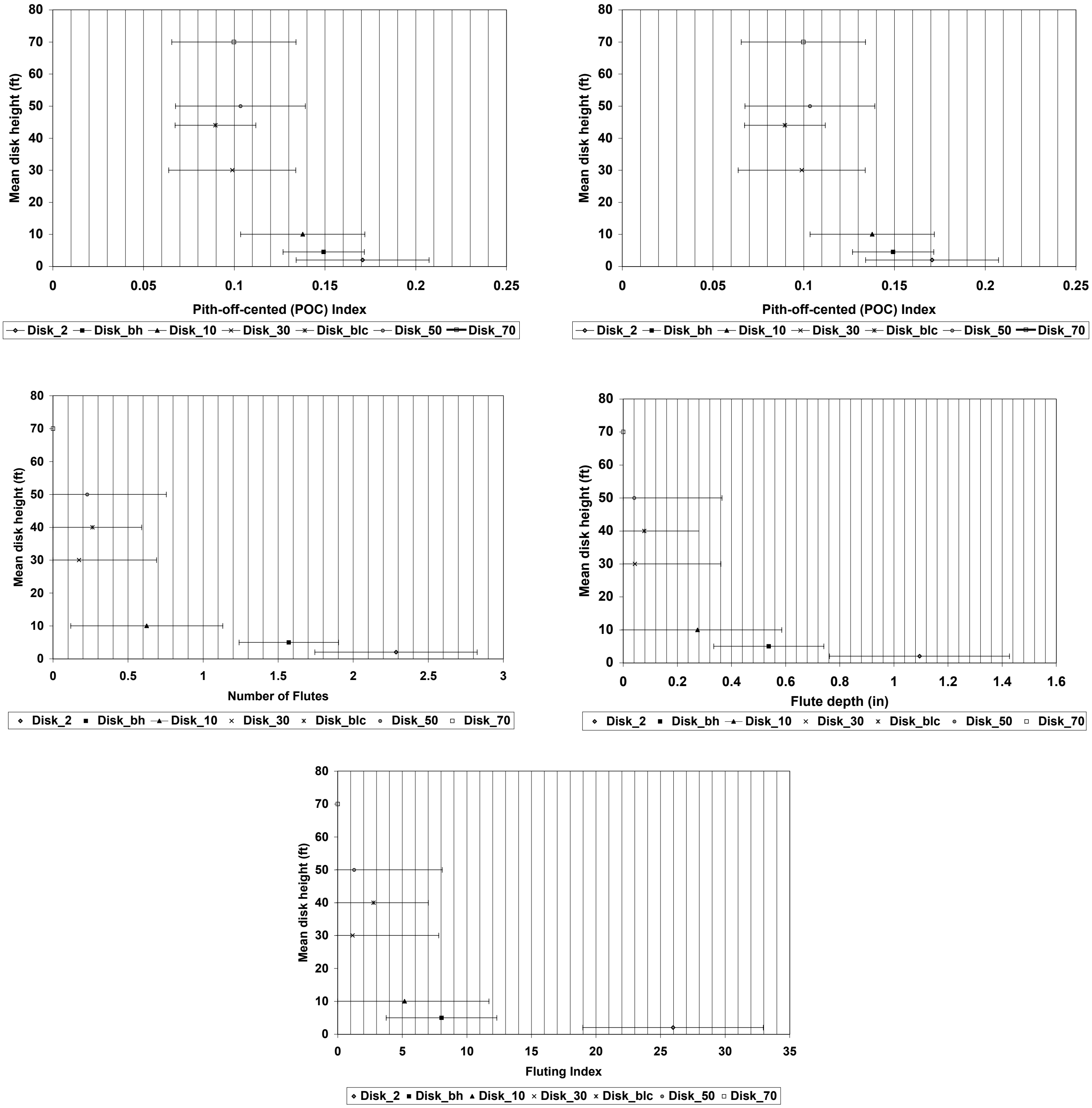


Figure 1 (a–e). Means and 95% confidence limits for eccentricity and fluting variables by disk height. Vertical axes represent mean height of each disk.

Correlation with Other Tree and Stand Attributes

Eccentricity

Out-of-roundness had a weak positive correlation with tree age but no significant linear relationship with any other stand or tree level variables (Table 5). POC had a weak negative association with site index and no relation with any other variables (Table 5).

Fluting

Older stands were associated with higher number of flutes, deeper flutes, and a higher fluting index (Table 5). Stands with more trees/ac were correlated with fewer and shallower flutes. Higher overall tree growth rates (MAI) were strongly related with higher number of flutes and deeper flutes, and showed some relation to higher levels of fluting index. Site index, PAI, and crown ratio showed no correlation with any fluting variables.

Discussion

Eccentricity

Out-of-Roundness

As with past studies with Douglas-fir (Reukema 1971, Williamson 1975) we found a tendency toward more out-

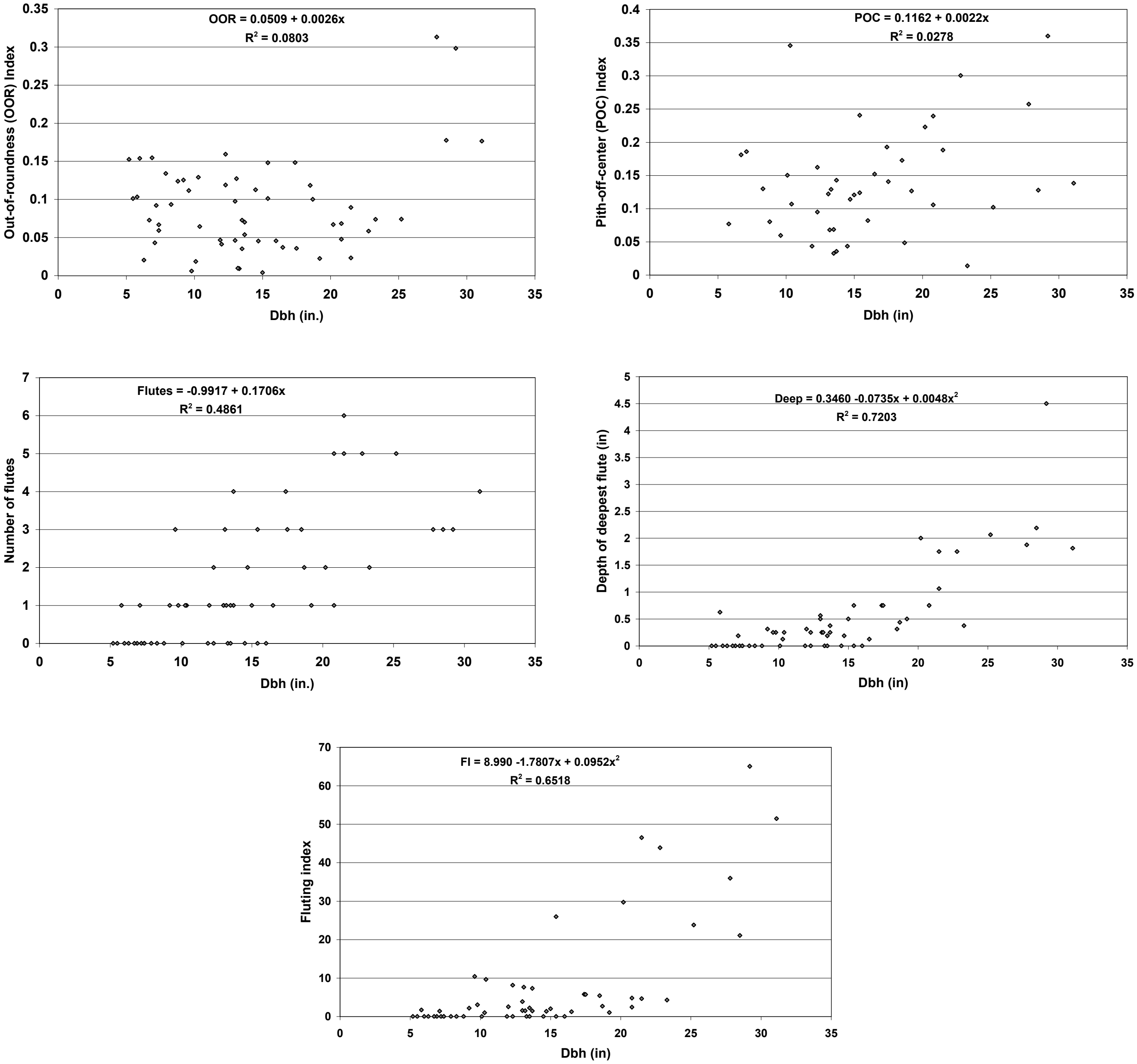


Figure 2 (a–e). Eccentricity and fluting variables vs. dbh using breast-height disks.

of-roundness in the lower portion than in the upper part of the stem. These trends were observed graphically and were supported with models resulting in statistically significant differences between the three lower log disks and some of the upper disks. This study showed, as a whole, that eccentricity on average decreased at a constant rate up the first one-third of the stem after which it remained stable. Kellogg and Barber (1981) found that the majority of their western hemlock study trees fell into two eccentricity categories: (1) decreasing eccentricity with increasing height and (2) constant level of eccentricity over the length of the stem. The Kellogg and Barber (1981) study trees were of similar age to the current study and selected from four coastal sites in British Columbia. One of the sites had wind-thrown sample trees that may in part explain why some of their study trees had eccentric cross-sections higher in the stem, but this is not necessarily clear from the study. Out-of-roundness values in the current study correspond closely with Williamson's (1975) values for mature Douglas-fir. The Williamson (1975) study found an average OOR of 0.123 and 0.0615 for basal and upper positions, respectively, while the current study averaged 0.109 for disk_2 and 0.0690 for disk_50.

We found weak evidence of a positive relationship between out-of-roundness and tree size (dbh). This is in agreement with Kellogg and Barber's (1981) findings but contrary to another study testing this factor for Douglas-fir (Williamson 1975). The precision of the model for this study could be improved with a larger sample in the upper diameter classes.

No other tree-level variables (age, growth rate, crown ratio) or stand-level variables (site, trees/ac) were correlated with out-of-roundness.

Table 5. Correlation coefficients of eccentricity and fluting variables with stand-level (age, tpa, site) and tree-level (MAI, PAI, crown ratio) attributes.

Variable		OOR	POC	Flutes	Depth	Fluting Index
Tree age	*r*	0.2488	0.1553	0.3522	0.4741	0.5341
	P-value	0.0620	0.2530	0.0072	0.0002	0.0001
Trees/ac	*r*	–0.0742	0.1466	–0.3064	–0.2606	–0.1828
	P-value	0.5904	0.2902	0.0229	0.0547	0.1816
Site class	*r*	0.0260	–0.2333	0.0448	0.0173	–0.0084
	P-value	0.8508	0.0895	0.7452	0.9001	0.9517
Mean annual increment	*r*	0.0205	–0.0188	0.4111	0.3562	0.2513
	P-value	0.8799	0.8904	0.0015	0.0065	0.0593
Periodic annual increment	*r*	–0.0109	–0.0740	0.1232	0.0696	0.0451
	P-value	0.9368	0.5948	0.3703	0.6135	0.7439
Crown ratio	*r*	–0.0258	–0.1157	–0.0088	–0.0674	–0.0511
	P-value	0.8491	0.3958	0.9480	0.6186	0.7060

Pith-Off-Center

The pith is the locus around which a core of juvenile wood is located. The wood in the juvenile core has shorter fiber lengths and higher microfibril angles than mature wood. In addition, wood density commonly changes with age from the pith; in western hemlock, juvenile wood (except for a few very dense rings adjacent to the pith) is slightly less dense than mature wood (Jozsa 1998). Because these differing properties may create various problems in processing and product performance, juvenile wood is generally considered inferior to mature wood for structural uses. The location of the pith, therefore, can influence the distribution of juvenile wood in the resulting sawed or peeled products. For dimensional lumber, logs having off-centered piths may yield a greater proportion of boards with intermixed juvenile and mature wood than would logs with centered pith; this could decrease grade recovery and net value since the grade of a given piece is limited by the poorest quality portion.

The current study showed on average a tendency towards more off-centered piths lower in the stem compared to the upper portion of the stem. Unfortunately, this is also the location of the largest logs and highest value products. A study looking more specifically at pith location related to value of actual sawn material may lead to more insight in this area. Tree size (dbh) had no relationship with off-centered piths. Stand density, stand age, site class, crown ratio or growth rate also could not account for a significant amount of variation in POC. Eccentricity (pith-off center and out-of-roundness) may be influenced more by other factors such as tree lean, slope, or wind that are not accounted for by the variables tested in this study.

Fluting

Changes in stem growth characteristics with increasing height above disk_2 were much greater for fluting than for eccentricity. Because most of the fluting was in disk_2 or below it, the fluting effects on recoverable lumber volume may be inconsequential: the most severely fluted portion of bole will be left on the stump at harvest and much of the rest of it will be lost as slabs when sawn. For these study trees we can assume the scaling cylinder for the first log would be in the vicinity of disk_30. The average diameter outside bark for disk_30 was 12.2 in. and 16.3 in. for disk_2. The depth of the deepest flute for disk_2 averaged 1.1 in. and only two of 24 observations were above 2.2 in., thus leaving flutes outside of the scaling cylinder except for on very rare occasions. Fluting would, therefore, impose more of a decrement in tree value if it occurred higher on the stem and closer to the scaling cylinder.

Fluting at any height still poses problems for peeling logs or debarking. In contrast to the current study, fluting at greater stem heights was documented in mature western hemlock stands in southeast Alaska (Julin et al. 1993a).

Flutes are often thought to originate at the base of trees and extend upward to some point in the stem. Day (1964) and Julin et al. (1993a), however, have presented the premise that flutes may be associated with branches in the lower crown. Julin et al. (1993a) theorized that as branches die they create a shortage of growth stimulants around the branch, suppressing localized radial development and thus initiating flutes. DeBell and Gartner (1997) discussed this hypothesis and presented evidence to the contrary for western redcedar, suggesting that flutes form at the base and extend upward. Our study supports the latter results because only minimal fluting was found at 30% and 50% relative height and crown base (43.6 ft–average height) (Table 3) where dying branches would likely be found. In addition, the deepest flutes were found at the base, and flutes were observed visually to exist between the spaces of the major root buttresses on these study trees.

In this study, tree size (dbh) had much stronger influence on fluting than eccentricity. The number of flutes at breast height increased at a constant rate with increasing dbh. All sample trees >16 in. dbh had at least one flute and all but one tree >22 in. dbh had at least three flutes. Both depth of deepest flutes and fluting severity (fluting index) increased at an increasing rate with dbh. These quadratic relationships, however, seemed to be driven by the relatively few large sample trees (>25 in.). A larger sample in this diameter class may be needed to better support this finding. It should be noted that size was accounted for in the calculation of both fluting index and count of flutes, thus moderating some aspects of differences between large and small trees in relation to manifestation of fluting characteristics.

Although Julin et al. (1993b) found that western hemlock trees on higher quality sites tended to have more severe fluting than on lower sites, we found site quality had no influence on fluting. Evaluation of sites based on wind severity may be the key factor here. Julin et al. (1993b) found that fluting severity was higher in coastal sites where wind was a prevailing factor, and further suggested that western hemlock trees on these sites were genetically predisposed to form flutes for stem strength and stability. The trees from our study were from coastal sites where wind is an influential component but no data were available that measured or rated wind on these sites.

We found that older trees tended to have more severe fluting than younger trees. Julin et al. (1993b) found that fluting of western hemlock trees in Alaska increased with age up to about 100 yr and then declined. The average tree in our study was less than 50 yr old. We found that the higher number of flutes were associated with lower stand densities (trees/ac). This agrees with DeBell and Gartner (1997), who found more fluting on trees at wider spacings for western redcedar.

Conclusions

Stem irregularities at breast height likely affect estimates of tree growth and stand density of western hemlock. Our study with eccentricity and fluting was not directed at quantifying measurement error or subsequent biases in volume estimates but showed that a certain degree of eccentricity and fluting exists at breast height. Researchers in eccentricity studies of other species have developed correction models (Biging and Wensel 1988) and suggested various noncircular geometric figures (Matern 1956) for more accurate estimation of cross-sectional area. Information from these studies could have useful application to the western hemlock individuals that exhibit severe eccentricity and fluting, for which typical measurement methods may introduce bias.

In general, both eccentricity and fluting are more apt to occur in the first log of a western hemlock stem compared to upper logs. Off-centered piths will influence the distribution of mature and juvenile wood and thus decrease the net value of end products, but the extent of the reduction remains to be determined. Forestry practices that produce larger diameter trees and more rapid growth or consist of more widely spaced stands and longer rotations will lead to more extensive fluting than those with smaller trees, slower growth, more narrow spacings, and shorter rotations; such practices and stand conditions will have little or no influence on eccentricity, however. Fluting poses a problem for debarking and peeling and would likely result in lower chip yields. Effects of fluting on recoverable volume and value from processing dimensional lumber, however, is minimal because flutes were found to rarely occupy the scaling cylinder.

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