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Effect of Habitat-Improvement Thinnings on Lumber Products from Coastal Douglas-fir

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Cover photograph: Timber-sale purchaser Robert Bateman measures a felled tree in preparation for bucking in an Oregon Coast Range Douglas-fir stand.

Abstract

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We selected 66 sample trees from two thinning treatments, each of which was applied at three sites on the Siuslaw National Forest in Oregon. The first commercial thinnings, conducted in 1992 and 1993, had been designed to accelerate the development of large trees with large branches and other old-growth characteristics so as to improve habitat for bird species that depend on such characteristics. Our sample trees, removed in commercial thinnings from 2008 to 2010, were felled and bucked into long (woods-length) logs whose stems were measured in detail, with surface defects also measured and located in three dimensions. Sample logs from the heavier of the two thinning treatments had larger knots on average than logs from the lighter thinning; they had higher average knot density and percentage of live knots. The long logs were "bucked" by computer simulation into short (mill-length) logs that were then "sawn" by computer simulation into lumber. Logs from the heavier thinning treatment had higher average lumber volume recovery, higher average lumber grade recovery, and higher estimated lumber value than logs from the lighter thinning. The analysis suggested that heavier thinning produced trees with more frequent and larger branches—more suitable for nesting and roosting by the target bird species—while at the same time yielding larger logs from harvested trees that produce higher product values. The product value from trees harvested in such thinnings is likely to be lower than values derived from harvests in nearby industrial forests, but comparable to other thinning treatments that are applied to similar forests on federal lands.

Keywords: Habitat-improvement thinning, stem analysis, surface knots, lumber quality, lumber volume, branch size, Douglas-fir lumber.

Summary

During the middle 1900s, a substantial amount of forest acreage in the Oregon coastal forest was clearcut and replanted, primarily to Douglas-fir (*Pseudotsuga menziesii* [Mirbel] Franco). As a result, large blocks of this forest exhibit little diversity with respect to dominant tree species, stand age, and structure. The Siuslaw National Forest, which occupies a substantial share of the central and northern coastal forest of Oregon, has launched an extensive thinning program intended to promote rapid development of late-successional conditions and improve habitat for old-growth-dependent wildlife species such as the northern spotted owl (*Strix occidentalis caurina*) and marbled murrelet (*Brachyramphus marmoratus*). Forest managers, both from government agencies and from private holdings, need to know what effect such thinnings might have on timber quality as well as how any changes in quality might affect revenues from timber sales.

This report describes an experiment that was designed to collect detailed stem and defect information on logs from trees harvested during a second habitat-improvement thinning conducted at three Siuslaw study sites. The stem and defect data thus obtained were used in simulation runs to evaluate products that might be manufactured from the logs—estimations of quantity, quality, and value from simulated sawing of the logs into lumber. Such information would be useful for foresters in estimating the value of standing trees, for loggers in estimating the value of the logs they harvest, and for sawmills in estimating the value of the logs they buy. The stem and defect data could be used to estimate the production and value of other forest products, given appropriate simulation software; or to evaluate the effects of thinning operations on stem and crown development in Douglas-fir. The treatments in the original 1992-to-1993 commercial thinning (phase 1) produced residual stocking densities of approximately 30 (treatment T30), 100 (treatment T100), and 60 (treatment T60) trees per acre. The second commercial thinning described in this later study (phase 2) involved further removals only from treatments T100 and T60. Overstory tree stocking on the treatment plots was reduced in the second thinning to about half of the relative density measured eight years after the first thinning.

We selected a sample of 66 Douglas-fir trees, which represented about 3 percent of the trees harvested in the thinning operations. This sample size is typical of wood-quality studies carried out by U.S. Forest Service scientists at the Pacific Northwest Research Station (Barbour et al. 1999, Lowell et al. 2012). The random sampling procedure used to select the sample trees was stratified so that all diameter classes were represented in the sample at about the same proportion as in the population of trees being harvested within each treatment plot and study site. The sample trees were felled, cut into long (woods-length) logs, and cable-yarded to landings as part of the normal thinning operation. A thorough stem analysis was

performed on each long log, with every knot or other potential product defect measured and located on the log in three dimensions. Stem characteristics such as sweep and crook were also recorded, and the inside-bark diameter of each log was measured at each assessment point along the stem. Three-dimensional data for the long logs were then converted into equivalent data for short (mill-length) logs using a bucking simulator developed for this study. The resulting data were then processed with AUTOSAW, a sawing simulator developed by the New Zealand Forest Research Institute, to estimate both the quantity and quality of lumber that could be recovered from the logs.[1] Lumber grades were assigned based on Western Wood Products Association rules for dimension and 1-inch Douglas-fir lumber. Product prices and equivalent tree and log values from recovered lumber were estimated and compared for the two thinning treatments. Below is a summary of the most important results from our analysis, emphasizing differences that can be attributed to thinning intensity.

Phase 1 Thinning Treatments and Diameter Measurements

- For trees measured immediately before the phase 2 thinning operations, the average diameter at breast height (DBH) from the treatment T100 plots in the phase 1 operations was found to be significantly smaller than the average DBH from the treatment T60 plots.
- Height and crown ratio were not found to have significant treatment effects. No significant differences were detected for any of the variables between subplots that were underplanted and those that were not, nor did we find any significant interactions between the underplanting and thinning treatments.

Sample Trees and Long Logs

- The 66 sample trees were bucked at the felling site into 185 long logs, of which 179 were recovered after yarding; 113 (63 percent) of the long logs recovered for measurement were from treatment T100 and 66 (37 percent) were from treatment T60. This is very nearly the same as the ratio of sample trees from treatment T100 (64 percent) to those from treatment T60 (36 percent).
- Treatment, DBH adjusted by treatment, and the position of the log within the tree were statistically significant predictors of long-log diameters and gross log volume; but for long-log length, only log position and an interaction between log position and adjusted DBH were significant. All means

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[1] The use of trade or firm names in this publication is for reader information and does not imply endorsment by the U.S. Department of Agriculture of any product or service.

and upper range limits of those variables were slightly larger for long logs from treatment T60 than from treatment T100.

- Sweep was recorded in 38 long logs, or 21 percent of the sample. All were butt logs. Treatment was not a statistically significant predictor of either maximum sweep offset (the distance to the center of sweep) even though both measures were slightly larger overall for logs from treatment T60 than for logs from treatment T100.
- Crook was recorded in only six long logs, four of which were from treatment T60 plots. Because crook often results from stem damage, the heavier thinning in treatment T60 may have contributed to the greater incidence of crook, but the sample was too small to support a firm conclusion.

Short Logs

- The 179 long logs recovered from the sample trees were bucked by a simulator into 327 short logs, of which 324 met the minimum diameter and length requirements for lumber production. The resulting short-log gross volume was 4,567.3 cubic feet; 19.6 discarded cubic feet were from three small unusable logs plus bucking waste, and 112.5 cubic feet were allocated to sawing trim. The loss to bucking waste and trim was 2.8 percent of gross available volume.
- Among short logs from the sample trees, treatment was a statistically significant predictor of large-end and small-end diameters and of gross log volume, but treatment had no apparent effect on log length. As with long logs, the position of the log within the tree and the DBH adjusted by treatment were significant predictors of short-log diameters and gross log volume. Log position was the only significant predictor of log length.
- Bucking reduced average sweep offset of 7.65 inches in long logs to only 1.94 inches in short logs, an amount that we concluded was unlikely to have much effect on product recovery.

Surface Defects

- In the 179 long logs for which stem profiles and surface defects were measured, a total of 11,022 defects were tallied. Of these, 10,970 were knots, with 41 percent classified as live knots and 59 percent as dead knots. The remaining 52 surface defects were small burls (44), forked tops (3), and surface scars (5). Only the knots and forked tops were judged to penetrate the surface of the log far enough to influence lumber quality when the log was sawn. Forked tops were treated in the sawing simulator as large knots.

- Trees from treatment T60 plots had more knots per tree, a higher average live-knot fraction, larger average and minimum knot diameters, and more knots per foot of merchandized stem than trees from treatment T100 plots. Trees from treatment T60 also tended to have larger DBH and longer stem lengths than those from treatment T100.
- Long logs from treatment T60 plots had larger average knot diameters and higher average knot densities in all three log-position classes (butt, middle, and upper logs) than long logs from treatment T100 plots. Within each major group, the smallest average knot density occurred in butt logs and the highest average knot density in upper logs, which typically represent the part of the tree within the living crown. Average knot diameter differed little between middle and upper logs and in some instances was larger in middle logs than in upper logs. It was always smaller in butt logs.
- As with long logs, in short logs the percentage of live knots and the average knot density were lowest in butt logs and highest in upper logs. Average knot density was also higher in short logs from treatment T60 than from treatment T100 except for butt logs. Average knot diameter was larger in logs from treatment T60 than in logs from treatment T100 for all position classes. The percentage of live knots was higher in upper logs from treatment T60 than from treatment T100 but lower in butt and middle logs.
- Regression analyses on the size of surface knots in tree stems, long logs, and short logs found no direct statistically significant treatment effect. However, DBH was significantly influenced by treatment and was also a significant predictor of knot size in tree stems, so we conclude that there is an indirect treatment effect. Results of the statistical analyses suggest that trees and logs with larger diameters tended to have larger knots except in the butt log; and live knots tended to have larger diameters than dead knots.
- Regression analyses on knot density in tree stems, long logs, and short logs found no statistically significant treatment effect. Again, because DBH was significantly influenced by treatment and was found to be a significant predictor of knot density, it can be argued that treatment indirectly influences knot density either through DBH directly or as an indirect effect of small-end diameter, which is closely correlated with DBH. Tree or log diameter and elevation were significant fixed-effect predictors except that for short logs, diameter was only significant in butt logs. For both long and short logs the live-knot fraction and the interaction between butt-log position and log diameter were significant fixed-effect predictors. For long logs, butt logs tended to

have lower knot densities than middle or upper logs and knot density tended to increase with log diameter and with live-knot fraction. For short logs, knot density tended to decrease with increasing butt-log diameter but was not influenced by diameter in middle and upper logs. For both log classes, knot density tended to increase as the percentage of live knots increased.

Lumber production

- The 324 merchantable short logs produced by the bucking simulator were processed into lumber using the AUTOSAW sawing simulator; 2,457 pieces of lumber were produced totaling 40,341.33 board feet. Logs processed from treatment T100 plots accounted for 59 percent of the lumber pieces and 58 percent of the lumber volume, with an average piece volume of 16.06 board feet. Treatment T60 produced a slightly higher percentage of wide pieces than treatment T100. The average lumber volume per piece from treatment T60 was 16.94 board feet, about 5 percent higher than treatment T100. Overall, treatment T60 produced 42 percent of the simulated lumber volume even though only 36 percent of the sample trees and 38 percent of the short logs came from treatment T60 plots.
- Because the percentage of wide pieces of lumber (larger than 8 inches) from treatment T60 was higher than treatment T100, the volume per piece was larger—5 percent overall and 9 percent in the higher lumber grades. As a result, the estimated average lumber values were also higher—about 10 percent higher for all grades and 11 percent for lumber from the higher grades. These differentials were even larger for select-structural lumber, the highest grade. Select-structural lumber from treatment T60 logs had 14 percent more volume per piece and 16 percent higher estimated value per piece than select-structural lumber from treatment T100 logs.
- The position in the tree from which the short log was taken had a substantial influence on both the volume and value of lumber recovered from the log. Butt logs produced much more of the higher lumber grades than middle or upper logs, with upper logs producing the lowest percentage of higher graded lumber (No. 2 and Better). Within all log-position classes, treatment T60 logs produced more lumber in the higher grades than treatment T100 logs. As a result, the average value per short log was 25 percent higher for treatment T60 logs. For butt logs the estimated value per log was 32 percent higher for treatment T60. Even for middle and upper logs, the differential between treatments was substantial; treatment T60 produced 20 percent

higher value for middle logs and 30 percent higher value for upper logs than treatment T100 produced for logs in the same position classes.

- Trees harvested from treatment T60 plots had 32 percent higher estimated value from recovered lumber than trees harvested from treatment T100 plots.
- Even though treatment T60 produced higher lumber volume recovery, grade recovery, and lumber value per tree and per log compared to logs from treatment T100, regression analyses found that treatment was a statistically significant predictor only for lumber grade recovery from short logs. However, a measure of diameter (either inverse DBH for trees or inverse small-end log diameter for short logs) was a significant predictor of lumber volume recovery, grade recovery, and lumber value recovery for both trees and logs. Because DBH was found to be strongly influenced by treatment, we conclude that the thinning treatment had an indirect influence on all the product recovery measures. Knot density, live-knot fraction, and average knot diameter were significant predictors of lumber grade and value recovery from trees and short logs. Log position and a measure of sweep were both significant predictors of lumber value recovery from short logs.

Stem Profiles and Branch Locations

- We were able to map long-log coordinates for profile points and knot locations into equivalent standing-tree coordinates for all logs from 37 of the 66 sample trees (56 percent); 11 of the trees had two long logs and 26 had three long logs. Partial data could be mapped for 21 of the remaining 29 trees. Logs from eight trees could not be mapped because none of their azimuth indicators could be read after yarding.
- Of the 179 long logs, azimuth indicators were readable on 132 (74 percent). These logs had 75 percent of the knots measured in the study—8,193 of 10,970 total knots.
- An exploratory statistical analysis of knot azimuths in the reconstructed tree stems gave mixed results. In some instances (for the Wildcat site and for the light and moderate thinning treatments on all sites combined), the analyses supported a conclusion that knots from the sample trees were not uniformly distributed around the boles but tended to cluster on the south-facing sides of the trees. In other instances (Cataract and Yachats sites) the hypothesis that knots are uniformly distributed about the boles of standing trees could not be rejected.

Contents

Introduction

For several decades after the mid-1900s, a substantial amount of forest acreage in the Oregon Coast Range was clearcut and planted to Douglas-fir (*Pseudotsuga menziesii*), involving nearly a third of the 630,000-acre Siuslaw National Forest as well as large tracts of other federal lands, forests managed by state agencies, and private holdings. The goal was to create forest plantations that would provide high yields of quality wood products over relatively short rotations. By the late 1980s, many coastal forests exhibited high tree density, little understory development, and low tree-species, stand-age, and vertical-structure diversity. The adoption of the Northwest Forest Plan (Haynes et al. 2006, Tuchmann et al. 1996) and other changes in federal policy that occurred in the early 1990s shifted the emphasis of federal-forest management from timber production to a new focus on protection, restoration, and enhancement of ecosystem functions and services. Current federal-forest management objectives for designated timberlands still include the production of forest products but within an overall framework designed to maintain or enhance the ecological integrity of forest ecosystems while also supporting forest-dependent social and economic systems (Barbour et al. 1997).

The Siuslaw has begun an extensive thinning program aimed at promoting rapid development of late-successional stage conditions in some of its even-aged plantations, in part to improve habitat for old-growth-dependent wildlife species such as the northern spotted owl (*Strix occidentalis caurina*) and marbled murrelet (*Brachyramphus marmoratus*).

To support this large-scale undertaking, U.S. Forest Service scientists at the Pacific Northwest (PNW) Research Station, working with national forest personnel and Oregon State University, established a set of study sites in the early 1990s to evaluate the effectiveness of thinning and underplanting regimes that had been designed to promote old-growth characteristics in Douglas-fir plantations (Anderson et al. 2007, Chan et al. 2006, Tucker et al. 1993), including larger but more widely spaced overstory trees (and thus fewer trees per unit of land area), improved vertical structure resulting from age classes (seedlings through midsized trees to mature trees), and multiple species both among the canopy trees and in the understory. This comprehensive, long-term research has come to be known as the STUDS project, an acronym formed from its title, the Siuslaw Thinning and Underplanting for Diversity Study. The underlying assumption of the STUDS project is that thinning the canopy will allow more light to penetrate into the stand so that residual trees retain more of their limbs and develop larger limbs of the type favored by the marbled murrelet for nesting and by the northern spotted owl and other species for roosting.

In Douglas-fir harvested from second-growth trees, the primary determinants of lumber grade, a measure of wood quality, are the percentage of juvenile wood and the frequency and size of knots (Barbour and Parry 2001), rather than the decay and other defects that characterize older trees. Young trees commonly have a much higher percentage of low-density juvenile wood and a smaller percentage of clear wood than older trees, primarily because their knots usually go all the way to the surface of the stem. In contrast, old trees have knots that are often buried deep within the stem so that the outer portion of the stem is mostly clear. For the residual trees in young stands, thinning tends to produce more juvenile wood because tree growth (especially diameter) accelerates, and more knots because more of their limbs are likely to be retained than they would be under a more closed canopy. The retained limbs also grow in diameter, increasing the size of knots in the lumber and potentially increasing the incidence of grade-limiting defects such as spike knots. Because Douglas-fir lumber is generally used in construction rather than for finished products, its demand is based largely on its inherent strength and stiffness—both of which can be compromised by excessive juvenile wood and the presence of knots (Briggs et al 2007). Thus, thinnings can reduce both the quality and the value of lumber derived from retained trees when they are finally harvested; this effect can increase over time with repeated thinnings and with more aggressive habitat-improvement treatments such as those used on the Siuslaw.

Despite the potential importance of juvenile wood in lumber produced from young Douglas-fir trees, we did not measure or account for it in this project because the methodology used to estimate lumber grades was not capable of incorporating information on juvenile wood. The methodology does, however, consider locations, density, and sizes of knots and other defects on lumber grade.

This report describes a phase 2 STUDS experiment that was designed to evaluate the quantity, quality, and value of lumber from trees left behind by habitat-improvement thinnings (1992 and 1993) on portions of three Siuslaw study sites (Chan et al. 2006). The trees sampled were harvested from 2008 to 2010 in a second commercial thinning.

History of the Study Sites

The plantations involved in the STUDS project were established in the early 1960s by clearcutting old-growth stands, broadcast burning and applying herbicides to inhibit competing vegetation, and planting Douglas-fir seedlings; in the mid-1970s, the plantations were precommercially thinned. They were selected as study sites for the STUDS project in the early 1990s and were commercially thinned in the autumn of 1992 and summer of 1993. The 1992-to-1993 operations are referred to as the phase 1 thinnings.

Before the phase 1 thinnings, each site was subdivided into four plots, with the boundaries of each following natural landforms, such as streams and ridges, to facilitate thinning operations on steep slopes. One plot at each site was designated an untreated control and the remaining three were randomly assigned to thinning treatments. From the initial stand densities of 223 to 277 trees per acre, the phase 1 treatments included heavy thinning (T30) to a residual density of 30 trees per acre, moderate thinning (T60) to a residual density of 60 trees per acre, and light thinning (T100) to a residual tree density of 100 trees per acre. Within each of the four plots, two 1-acre subplots were established, one of which was randomly selected for underplanting with Douglas-fir and western hemlock (*Tsuga heterophylla* [Raf.] Sarg.). All overstory trees in the 1-acre subplots were tagged with identity numbers unique to the site; 40 of the tagged trees within each subplot were selected as overstory measurement trees, meaning that all trees were designated as measurement trees in the T30 plots. Total tree height, height to live crown, and diameter at breast height (DBH) were measured before the phase 1 thinning, immediately after thinning, four years after thinning, and eight years after thinning (Chan et al. 2006).

The principle focus of this report is the phase 2 thinnings. The logging operations for this second commercial round of thinnings were carried out primarily in 2008 and 2009 and the final logs were processed and sold in 2010. A complete set of measurements, including DBH for all trees within each 1-acre subplot, was taken between January and May of 2008, shortly before the thinning operations began. For the designated overstory measurement trees, total tree height and height to live crown were also measured. Siuslaw personnel also conducted a timber cruise that included the 1-acre subplots and their surrounding treatment plots.

Research Objectives

The objectives of the wood-quality assessment for phase 2 of the STUDS project were to:

- Develop and implement procedures for acquiring detailed stem and defect information to be used in a sawing simulator to estimate the quantity, product sizes, and grades of lumber from the thinning operations
- Compare the size and frequency of lumber defects (primarily knots) in trees harvested from the moderate-thinning and light-thinning plots; note that some of what are considered **defects** from the perspective of forest products manufacturing could be considered **assets** in the context of habitat-improvement thinnings, because larger knots suggest the successful development of larger limbs on residual trees

- Compare differences in lumber quantity, quality, and value from trees harvested from the moderate-thinning plots versus trees harvested from the light-thinning plots
- Develop a dataset that includes three-dimensional coordinates of stem profiles, branch locations as indicated by surface knots, and stem-surface defects of each sample tree as it stood before felling

Study Design and Preparation

Description of Study Sites

The three STUDS stands—Cataract, Wildcat, and Yachats (Chan et al. 2006)—lie on the western slope of the Oregon Coast Range at elevations ranging from 400 to 1,200 feet above mean sea level (fig. 1). Treatment plots on the two southerly sites (Cataract and Yachats) have northwest to northeast aspects whereas the treatment plots on the northern site (Wildcat) face southwest. Overstory trees on the three sites are essentially all the same age, part of plantations established from 1960 to 1962.

Figure 2 shows the operational layouts of the three STUDS study sites and the locations of the treatment plots, T100 and T60, that were scheduled for a second commercial thinning—the other two plots from the first (phase 1) thinning, T30 and the control, are excluded. The trees on the T30 plots had not yet reached the target basal area that would trigger another thinning and the control plots are intended to remain untreated. All three sites were logged with cable systems except for a small area of ground skidding on the Yachats site (fig. 2). The figures also show the locations of sample trees taken from the 1-acre subplots.

Thinning Treatments

Phase 2 of the STUDS project was designed to build on information from the phase 1 T100 and T60 plots (Anderson et al. 2007). The phase 2 thinnings on these plots were designed to further reduce the relative density of overstory trees to about half of the relative density measured in the year 8 assessment following the phase 1 treatments. Relative density is calculated as $BA/\sqrt{QMD}$, where BA is the basal area per acre and QMD is the quadratic mean diameter of the overstory trees on the plot (Curtis 1982). Although the T30 plots from phase 1 were not treated in phase 2, they will continue to be measured at intervals as part of the continuing assessment process (Anderson et al. 2007).

Before thinning operations began, we conducted an assessment of all residual overstory trees on the plots from phase 1 treatments T100 and T60, primarily to

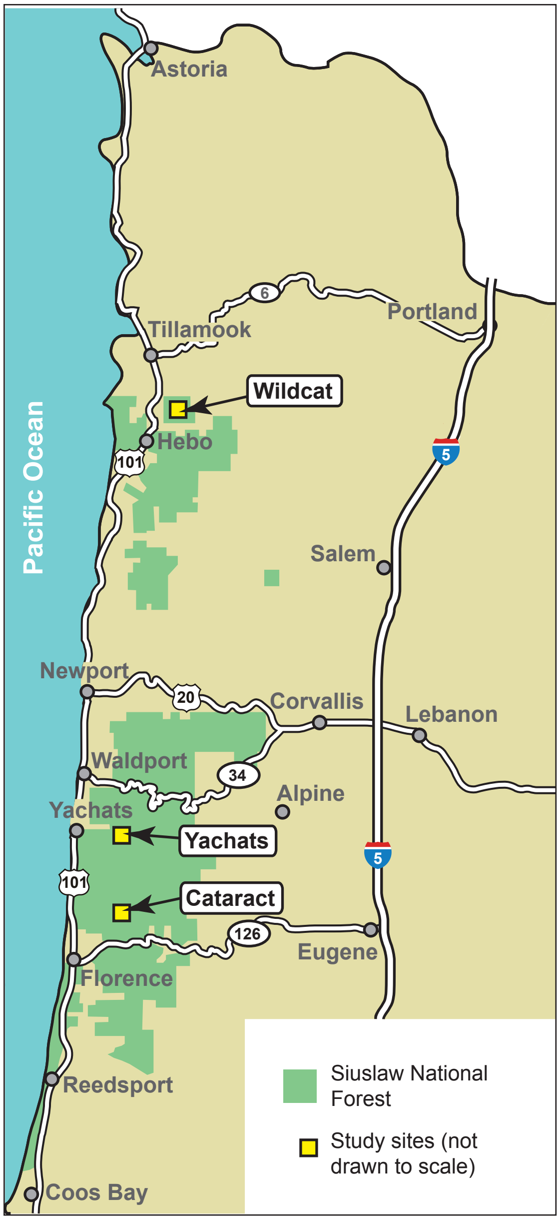

Figure 1—Location map for three wood-quality study sites (Cataract, Wildcat, and Yachats) on the Siuslaw National Forest where sample trees were harvested from 2008 to 2010—15 years after habitat-improvement thinning treatments (Chan et al. 2006).

provide data that would signal the existence of significantly different characteristics that might have been caused by the different thinning intensities (a long-term focus of the STUDS project). Our results (table 1) were consistent with those of Chan et al. (2006), who analyzed data measured midway between the phase 1 and phase 2 treatments. Like Chan et al. (2006), we found that DBH differed significantly

Figure 2—Operational layout for three wood-quality study sites established on Douglas-fir stands in the Siuslaw National Forest 15 years after habitat-improvement thinning treatments: (A) the Cataract site northeast of Florence, (B) the Wildcat site north of Hebo, and (C) the Yachats site east of Yachats. North is toward the top in each map.

between the treatments but we did not find a detectable effect on total tree height or crown ratio (the percentage of tree height that constitutes the living crown). For crown ratio, Chan et al. (2006) suggested that a trend could be developing, with crown ratio in lightly thinned stands tending to decrease over time. We found that although the effect was not significant at $\alpha = 0.05$, it would be significant at $\alpha = 0.10$ ($p = 0.0933$) with the larger average crown ratio corresponding to trees from the more heavily thinned plots. We modeled DBH, height, and crown ratio using linear mixed-effect models that were based on a split-plot design with (1) fixed effects for thinning treatment, underplanting, and an interaction term for thinning by underplanting; and (2) random effects for sites, thinning (sites), underplanting (thinning sites) and trees (underplanting thinning sites). Using SAS® 9.4 (2013) PROC GLIMMIX with the Kenward-Rogers degrees of freedom adjustment, we found that the only strongly significant difference was for average DBH ($p = 0.0088$), which was significantly smaller for trees from the T100 plots than from the T60 plots. No significant differences were detected for any of the variables between subplots that were underplanted and those that were not, nor were there any significant interactions between underplanting and thinning treatment. As a result, for the remaining analyses we did not differentiate between trees from subplots that were underplanted and trees from subplots that were not. The importance of site was determined from a combined covariance test for random effects and was significant for all three response variables: DBH, height, and crown ratio (table 1). Although these results are not part of the present study, we present them here because they demonstrate the effects of the two thinning treatments 15 years after the first commercial thinning and just before the beginning of the present study.

Selection of Sample Trees

To maximize the utility of data obtained for our wood-quality assessment, we opted to collect detailed stem form and defect information on the harvested logs rather than conducting a conventional sawmill recovery study. Stem form and defect data can be used in simulation experiments to evaluate a variety of products that might be manufactured from logs. In this report we estimate the quantity, quality, and value of output from the simulated sawing of the logs into a standard Douglas-fir lumber assortment. Given suitable simulation software, the same logs could be repeatedly sawn by simulation using different sawmill or lumber parameters, or converted by simulation into veneer and other products.

We selected a stratified random sample representing about 3 percent of the trees harvested in the phase 2 thinning operations on the three study sites. The 3-percent sample is typical of wood-quality studies carried out by the PNW Station (Barbour et al. 1999, Lowell et al. 2012). Selection of sample trees was based on data from the

Table 1—Effects of light (T100) and moderate (T60) treatments on Douglas-fir stands in the Oregon Coast Range 15 years after commercial thinning treatments

	T100[a]		T60[b]				
Response variable	Number of trees	Mean (SE)	Number of trees	Mean (SE)	Treatment difference (95 percent CI)	Treatment difference	Site importance
DBH (inches)	558	17.61 (0.3992)	298	19.40 (0.4178)	1.79 (0.66, 2.93)	0.0088	< 0.0001
Height (feet)	243	110.63 (5.1141)	219	111.94 (5.1213)	1.31 (-3.62, 6.24)	0.5395	< 0.0001
Crown ratio	243	0.368 (0.0199)	219	0.447 (0.0200)	0.079 (-0.033, 0.192)	0.0933	< 0.0001

DBH = Diameter at breast height.
SE = Standard error.
CI = Confidence interval.
Crown ratio is the ratio of the length of a tree's crown to its total height.
[a] Stand reduced to approximately 100 trees per acre.
[b] Stand reduced to approximately 60 trees per acre.

presale timber cruise and is summarized in table 2. Trees measured in the timber cruise were stratified into five DBH classes within each treatment plot, with the lowest and highest classes being open ended (table 2). Given that 2,028 trees were scheduled for removal during the thinning operation, a 3-percent sample would comprise 61 trees but we decided to select 66 trees as a hedge against breakage or losses during harvesting. The sample was stratified in proportion to the number of trees in each DBH class to be harvested within each treatment plot (table 2), with the stipulation that at least one sample tree be selected from each DBH class that was scheduled for tree removal within each treatment plot. For selection purposes, the subplot trees scheduled for removal in the thinning were sorted into the five DBH classes within each treatment plot based on measurements recorded during the 2008 assessment of overstory trees. For each DBH class in each treatment plot, the specific trees to be included in the sample were then randomly selected from the population of trees scheduled for removal from the 1-acre subplots.

The cruise results (table 2) indicated that four treatment plots—two in Cataract, one in Yachats, and one in Wildcat—each had no trees designated for removal in one DBH class; thus, no sample trees could be selected from that DBH class in those plots. Five trees selected as sample trees through the random-selection process proved to have been marked as "leave trees" that were to be retained in the post-thinning stand. For these, we substituted a sample tree that was in the same study site and that had as nearly as possible the same DBH as the originally selected tree. For example, one treatment plot (T100 in Wildcat) had only a single tree in the 23+ DBH class on the two subplots, and although it had been selected as a sample

Table 2—Sample trees selected by stratified random sampling based on DBH distributions to test the effects of light (T100) and moderate (T60) thinning treatments on Douglas-fir stands in the Oregon Coast Range 15 years after commercial thinning

					Sample trees (stratified random sample)		
Study site (treatment)[a] and size of area thinned	DBH class	Mean DBH	Mean estimated total height	Trees scheduled for removal	Total	By DBH class	ID tag numbers of sample trees selected by DBH class from the two 1-acre subplots within each treatment
	- - - - *Inches* - - - -		*Feet*				
Cataract (T100) 6.5 acres	< 10	9.9	89.0	13	13	1	1656
	10-14	12.4	101.5	90		3	1009, 1035, 1013
	14-18	15.6	111.1	210		6	1655, 1570, 1110, 1514, 1580, 1211
	18-23	19.8	116.1	120		3	1501, 1217, 1158
	≥ 23[b]	—	—	—		0	—
Cataract (T60) 7.5 acres	< 10[b]	—	—	—	7	0	—
	10-14	13.1	97.0	12		1	2604
	14-18	16.3	111.7	70		2	2154, 2019
	18-23	19.6	112.5	114		3	2146, 2568, 2241
	≥ 23	25.3	125.0	9		1	2041
Wildcat (T100) 6 acres	< 10	8.9	54.0	5	10	1	1247
	10-14	12.5	73.0	57		2	1017, 1254
	14-18	15.7	94.2	170		5	1285, 1867, 1008, 1226, 1295
	18-23	19.7	108.6	65		2	1723, 1504
	≥ 23[b]	24.5	107.0	9		0	—
Wildcat (T60) 6 acres	< 10[b]	—	—	—	9	0	—
	10-14	13.1	79.5	20		1	2133
	14-18	15.9	92.5	99		3	2739, 2114, 2658
	18-23	19.6	100.3	111		3	2604, 2042, 2687
	≥ 23	23.3	116.0	2		2	2732, 2607
Yachats (T100) 16 acres	< 10	9.0	81.0	6	19	1	1626
	10-14	12.7	88.1	58		2	1633, 1041
	14-18	16.7	101.8	181		5	1603, 1727, 1114, 1560, 1140
	18-23	21.0	113.9	329		9	1202, 1076, 1611, 1659, 1600, 1604, 1016, 1588, 1111
	≥ 23	24.1	116.6	46		2	1159, 1708
Yachats (T60) 7 acres	< 10[b]	—	—	—	8	0	—
	10-14	12.9	83.5	11		1	2735
	14-18	16.0	104.2	56		2	2722, 2022
	18-23	20.7	110.8	132		4	2532, 2122, 2733, 2002
	≥ 23	24.6	108.7	33		1	2062
Totals				2,028	66	66	

DBH = diameter at breast height.

[a] Stand reduced to 100 trees per acre in T100; stand reduced to approximately 60 trees per acre in T60.

[b] No sample trees were selected in these diameter classes because none were available in the unit and treatment area being sampled.

tree, it was marked in the field as a leave tree. Therefore we substituted a second sample tree in the 23+ DBH class from the other (T60) Wildcat plot, which had been scheduled for only a single sample tree in that DBH class. This means that the moderately thinned plot had one more sample tree than selected through the stratified random sampling process, and the lightly thinned plot correspondingly had one less sample tree.

Table 2 also shows the tag numbers of all sample trees in the final wood-quality sample. Each sample tree was marked in the field as shown in figure 3 with information indicating the study site and treatment type, the unique tree identification number, DBH, and the north and south cardinal directions (reference points for evaluating possible relationships between direction and the frequency and size of knots).

Field crews also recorded the azimuth and distance from each sample tree to one of the corners of its subplot. Coordinates of the subplot corners were established using a survey-grade geographical positioning system (GPS) and differential

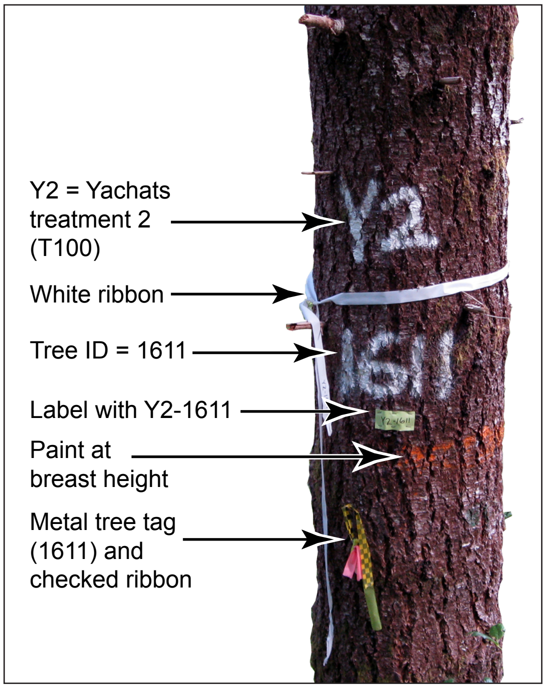

Figure 3—A sample tree in one of three wood-quality study sites established on Douglas-fir stands in the Oregon Coast Range 15 years after habitat-improvement thinning treatments; the Y2 designation indicates that the tree was in the Yachats study site (as opposed to Wildcat or Cataract) and that the treatment (T100) was a light thinning leaving 100 residual trees per acre (the moderate T60 treatment would have been designated by Y3 rather than Y2).

correction. These coordinates were used to calculate the coordinates of the tree as an offset from a subplot corner, enabling the plotting of all sample trees in the correct locations within their respective subplots (fig. 2).

Data Collection

Procedures for product-recovery studies have been developed through more than 100 such studies conducted over nearly 50 years at the PNW Research Station. Commonly, such studies involve collection of data in four phases:

1. Tree data, collected when the tree is standing: Information recorded includes the location of each tree, ownership, DBH, estimated height, and other parameters that might be considered relevant for a particular study.
2. Long-log (woods-length) data, collected when logs are bucked from the tree stem at the harvesting site: Their lengths are determined by the logger according to the purchaser's requirements and any specifications that have been stipulated in the timber-sale agreement. For this study, data were also collected on stem form and surface defects.
3. Short-log (mill-length) data, usually collected when long logs are bucked at the mill where they will be processed according to purchaser requirements: For this study, long logs were bucked into short logs using computer simulation instead of being followed into the mill as would have been done in a conventional product-recovery study. Data from the simulated short logs were used as inputs into a sawing simulator.
4. Product data, collected when short logs are sawn: In a conventional product-recovery study, each sample log is converted into products in a mill and the individual pieces produced are tallied and graded to calculate the recovery of quantity and quality for each log and for the collection of sample logs as a whole. For this study, the AUTOSAW sawing simulator (FRI 1994, Todoroki 1990) was used instead to simulate the process of converting each log into lumber. The sawing simulator was calibrated (Barbour et al. 1999, Todoroki et al. 2005) to estimate the grade of each piece of lumber according to U.S. grading rules for Douglas-fir lumber as described in WWPA (2005).

Long-Log Measurements

Felling and bucking—

At each study site, the sample trees were felled and bucked by the timber-sale purchaser in advance of the main thinning operation at that site. As each tree was felled and bucked into long logs (fig. 4), labels identifying the study site, treatment,

Figure 4—At one of three wood-quality study sites established on Douglas-fir stands in the Oregon Coast Range 15 years after habitat-improvement thinning treatments, timber-sale purchaser Robert Bateman (A) felling a sample tree (Y2-1159)—note that although this tree was in a lightly thinned plot (residual tree density 100 trees per acre), the understory appears to have responded well to thinning—and (B) measuring a felled tree in preparation for bucking.

tree, and long log were written in indelible ink on heavy, water-resistant paper and fastened with aluminum staples to both ends of each log (fig. 5). These measurements were recorded separately as were two inside-bark diameter measurements taken at right angles on each end of the log and recorded to the nearest 0.1 inch, and length recorded to the nearest 0.1 foot. These measurements were intended primarily to help identify sample logs if labels were destroyed or numbers and letters became unreadable during yarding; final diameter and length measurements were postponed until the stem analysis.

As the sample trees were being bucked into logs, a horizontal line was painted at the top of one side of each log, and a compass reading (N, NE, E, SE, S, SW, W, or NW) was added to indicate the orientation of that side of the log when the tree was standing; 132 of the 179 long logs that were measured had readings that could be recorded as the logs were being measured. The paint used for these marks did not always survive the yarding operation, often because large sections of bark were dislodged. In addition, the paint that was originally selected was ineffective when applied in the rain; in the latter part of the study, this was corrected by recording compass readings on the log labels (fig. 5). Some identifying information almost

Figure 5—Part of a log from a sample tree harvested on Douglas-fir stands in the Oregon Coast Range 15 years after habitat-improvement thinning treatments. The label (stapled to the end of the log when it was cut) indicates the side of the stem that faced south (S with arrow) before the tree was felled, that the tree was from plot 3 on the Cataract study site (and thus from treatment T60 with a residual density of 60 trees per acre), and that this was log 1 (the butt log) from tree 2154.

always survived yarding; in fact, only a single log (C3-2041-3) had unreadable labeling and had to be identified by the measurements recorded separately during felling and bucking. However, five sample logs that were measured during felling and bucking were never found at the log yard. Either those logs were broken during yarding and never reached the landing, or they arrived with no labels and no staples, paint, or other marks that would have identified them as sample logs. Each of these lost logs was the topmost log cut from the tree, and all had small-end diameters less than 4 inches.

Stem profiles and surface defects—

During the yarding process, the sample logs were segregated from other logs as they arrived at the landing, then moved to the purchaser’s log yard (Cataract and Yachats sites) or to a roadside clearing (Wildcat site); there they were placed on bunk logs so they could easily be measured and the entire log surface inspected. Figure 6 shows several sample logs rolled out for measurement at the Wildcat site.

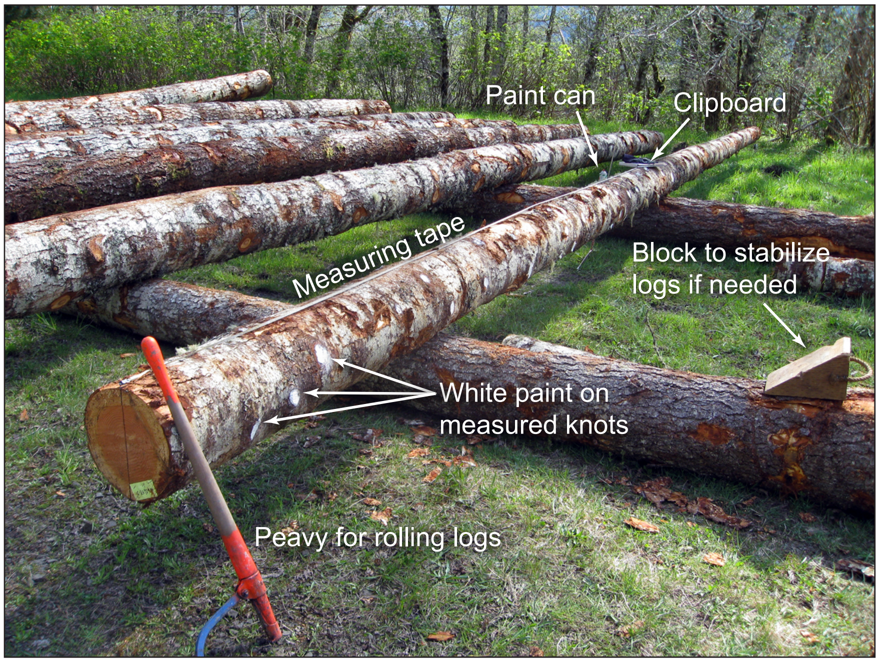

Figure 6—Stem analysis on sample logs from a sample tree harvested on Douglas-fir stands in the Oregon Coast Range 15 years after habitat-improvement thinning treatments. Data were recorded along the full length of each log in an initial (0°) orientation, then the log was rolled 180° and defects not visible in the initial orientation were measured and recorded.

A Modified Procedure for Measuring Long Logs

Data collection procedures used previously at the PNW Research Station to acquire stem data for sawing simulations (Barbour et al. 1999) require a minimum of two people working together. For this study we modified those procedures into the following five-step procedure to allow one person working alone to collect stem data. All measurements are recorded to the nearest 0.1 foot or the nearest 0.1 inch.

Step 1. Establishing reference points and lines—
On each end of the log, draw an approximately vertical line through the pith and extend it to the perimeter (fig. 7). This line serves as a reference for measurements and is helpful as a guide when rolling logs that have shape irregularities. It is taken as the y-axis, with the axis perpendicular to it taken as the x-axis, and the imaginary line joining the geometric centers of the two ends of the log taken as the z-axis. Drive nails into the log at points A and B in figure 7 and, starting at the large end of the log, lay a measuring tape along the distance (labeled the longitudinal axis) between points A and B. Affix a chalk line from point A to point B and draw it tight. This line serves as a

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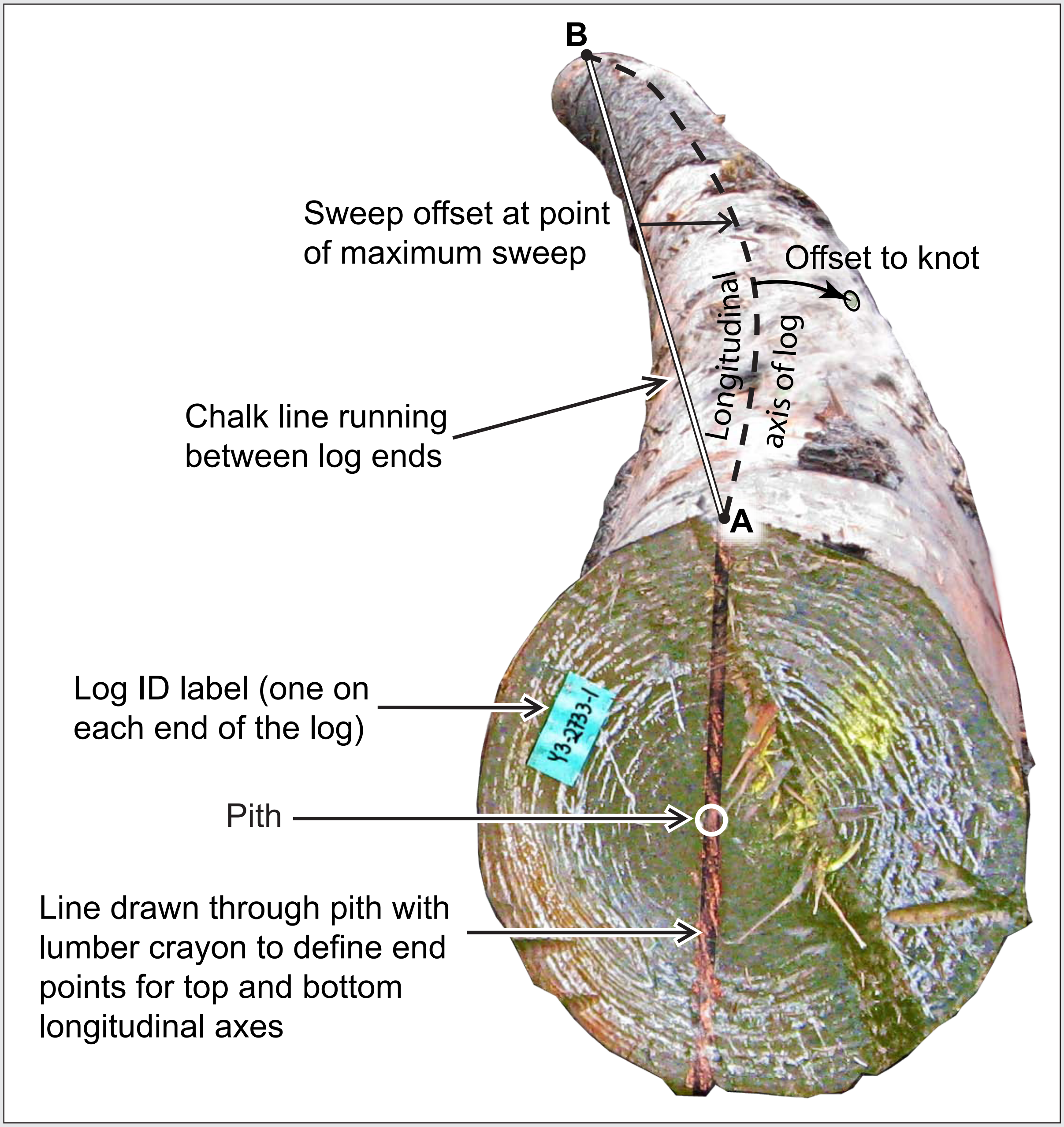


Figure 7—Measurements taken on stem profiles and surface defects of logs from a sample tree harvested on Douglas-fir stands in the Oregon Coast Range 15 years after habitat-improvement thinning treatments. Length measurements were taken to the nearest 0.1 foot, whereas offset and diameter measurements were taken to the nearest 0.1 inch.

From p. 14

reference for measuring sweep and crook offsets (steps 4 and 5 below), and is assumed to be parallel to the z-axis, which joins the two geometric centers of the log ends.

The orientation of the log when the reference points and lines are established initially is known as the 0° orientation. For logs with sweep, this orientation is such that the maximum sweep is positioned in either the vertical or horizontal plane and thus can be measured as up, down, left, or right from the central axis of the log as viewed from the butt. For example, the log in figure 7 sweeps to the right from its central axis. When the log is rolled to measure surface defects on its other side, the new orientation is referred to as the 180° orientation.

Step 2. Measuring knots and other surface defects—
To facilitate measurements and verify whether a defect exists at any point, it is often necessary to remove bark around suspected surface defects. This is particularly true where knots are fully overgrown by bark. At each point along the log where a defect occurs, measure the offset distance from the longitudinal axis to the center of the defect along the arc of the log surface (fig. 7), and note whether it is left or right of the longitudinal axis when viewed from the large end of the log. Also record the distance along the measuring tape (longitudinal axis) to the point that corresponds to the center of the defect.

Working along the log in two directions—parallel to the longitudinal axis of the log and perpendicular to that axis—measure all surface defects at least 0.5 inch in average diameter unless they will most likely be trimmed off with the outer slab and thus not penetrate into lumber sawn from the log (this sometimes occurs, for example, with small burls that form on the surface of a Douglas-fir tree). If the defect is a knot, record whether it is alive (sound) or dead (unsound). Live knots, also known as ingrown or tight knots, have fibers that are largely intergrown with the fibers of the surrounding xylem. Dead knots usually have a visible separation between the knot and the tree stem, or they may appear somewhat decayed at the surface. The distinction between live and dead knots is important as it influences the grade of lumber manufactured from the log.

After each surface defect is recorded, spray it with white paint (fig. 6) to indicate that the measurement has been completed and insure against double counting.

Step 3. Measuring log diameters—
Measure inside-bark diameters on each end of the log, one along the vertical line drawn in step 2, and the other perpendicular to that line with the measuring tape placed so that it passes through the pith. For butt logs, use calipers to measure the horizontal diameter inside bark at a point 4 feet from the large end of the log. This additional measurement, specified in the Forest Service cubic scaling rules (USDA FS 2002), helps reduce inaccuracies associated with butt swell near the base of the tree.

Use calipers to measure an inside-bark diameter at each point on the longitudinal axis of the log corresponding to the location of a surface defect. If knots are clustered closely together, use one diameter measurement. If log cross sections are elliptical rather than round, measure both horizontal and vertical diameters at each point to improve the accuracy of the sawing simulation. Make sure that inside-bark diameter measurements are no farther apart than 4 feet as measured along the longitudinal axis of the log; if necessary, take one or more intermediate measurements.

Step 4. Measuring sweep and crook—
Sweep is a curvature that extends along the entire length of the log, causing the longitudinal axis of the log to deviate from a straight line; sweep can be uniform with the maximum sweep occurring at the center of the log, or nonuniform with the maximum sweep occurring at a point nearer one end of the log. A crook is a curve or bend in a log, often abrupt, that extends only over part of the log length. A single log can have multiple crooks.

With the log in the 0° orientation, measure the offset as a perpendicular from the chalk line to the longitudinal axis of the log (fig. 7) at the point of maximum offset, as measured along the longitudinal axis from the large end of the log and as viewed from the large end of the log. For crooks only, measure the length of the crook along the longitudinal axis of the log from the crook base toward the top of the tree. Note whether the offset direction is right, left, up, or down. Only record sweep and crooks when the maximum offset is 2 inches or more.

Step 5. Measuring surface defects after the log has been rolled—
Roll the log 180° and use blocks, if needed, to stabilize the log in the new position (fig. 6). Drive nails into the log as shown in figure 7 at points A and B and, starting at the large end of the log, lay a measuring tape along the distance (labeled the longitudinal axis) between points A and B. Measure each surface defect that has not yet been sprayed and its offset as described in step 2. Measure log diameter at the location of each newly detected surface defect as described in step 3 above.

Preparation and Organization of Data

Measurements from the various phases of fieldwork were entered into Microsoft Excel® spreadsheets, verified, and processed with additional software in preparation for the sawing simulation. Several utility programs were developed to convert data from the Excel spreadsheets into text files that conform to AUTOSAW requirements. This section describes the process by which data were entered, verified, and reformatted (fig. 8).

Data entry and verification—

The profile and defect data for each log were entered into a single Excel worksheet (fig. 8). All worksheets (and thus all data for the long logs) for each site (Cataract, Wildcat, or Yachats) were collected into a single Excel file for that site. Worksheets within the files were named using the long-log nomenclature as shown in figure 5; for example, C3-2154-1 represents the first (butt) log from tree 2154 in the moderately thinned plot (designated by 3) on the Cataract study site (designated by a C). The second long log from the same tree is C3-2154-2.

Measurements were verified by entering the set of profiles and surface defects for each log a second time into a verification worksheet within each Excel file. The verification worksheet used Excel formulas to compare each measurement as it was entered into the verification worksheet with the measurement from the corresponding cell of the original worksheet. Any discrepancies were displayed as errors so that they could then be investigated and reconciled with the original, hand-written data sheet.

System requirements for STUDS utility software—

Checking software requirements, simulating log bucking, and converting data to the AUTOSAW format (fig. 8) all required the development of special utility software capable of reading and writing Excel files. These utility programs have the following requirements:

- The operating system on the user's computer must be Windows XP with Service Pack 3, or any later version of Windows® (such as Vista, 7, 8, or 10). Earlier versions of Windows and versions of Windows XP without Service Pack 3 are not supported.
- The Microsoft® .NET Framework 4.0 or a later version, in either the client version or the full framework, must be on the user's computer. Version 4.0 of the .NET Framework can be downloaded at no cost, but administrative privileges are required to install it. The client profile is a much smaller download than the full framework and is adequate for all of the STUDS utility programs. Version 4.0 of the Microsoft .NET Framework can only be

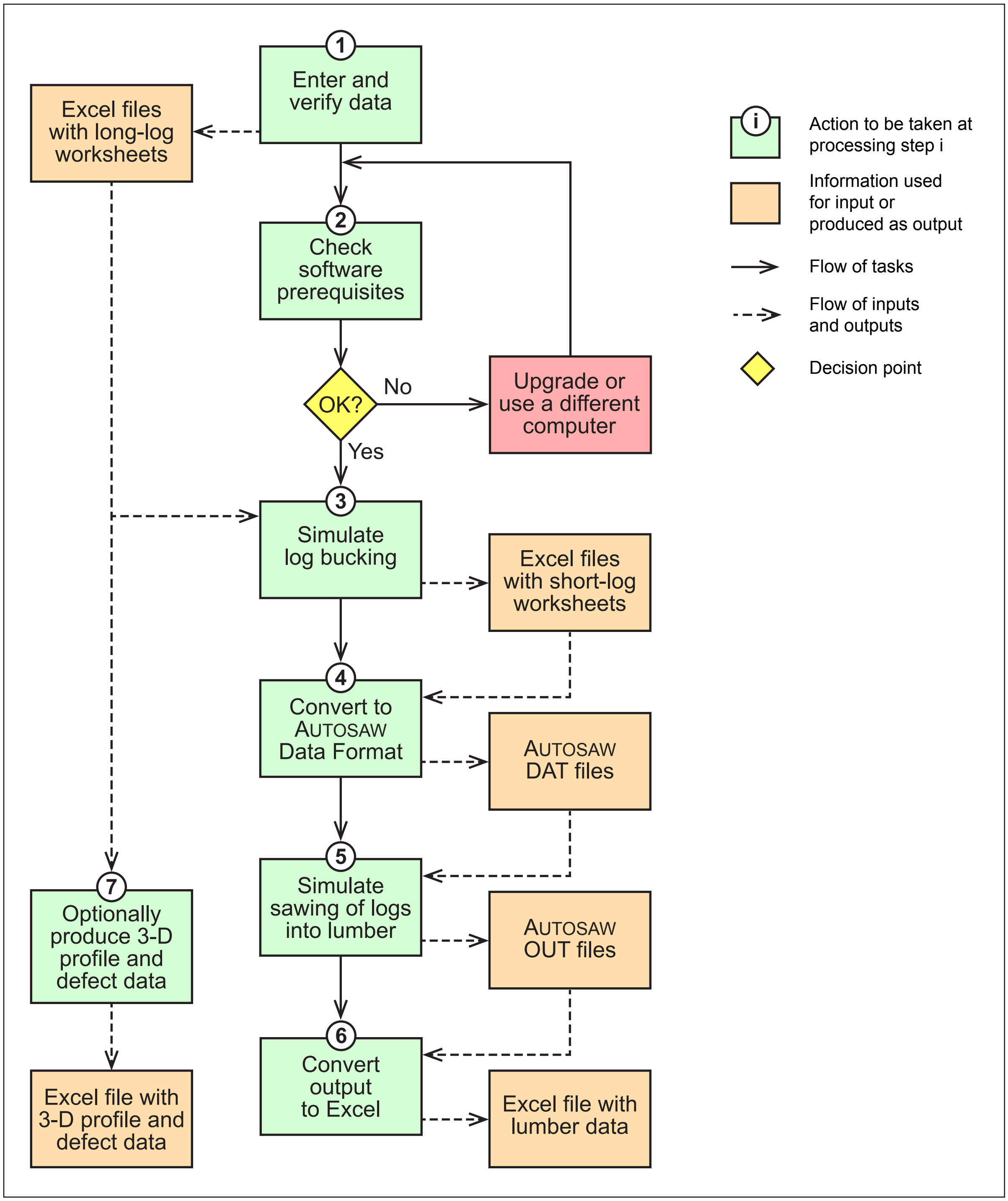


Figure 8—Steps followed to prepare and organize data for the analysis wood quality in long logs, short logs, and lumber produced from sample trees harvested on Douglas-fir stands in the Oregon Coast Range 15 years after habitat-improvement thinning treatments.

installed on a computer running Windows XP with Service Pack 3 or any later version of Windows.

- Most of the STUDS utility programs require Microsoft Excel 2002 or a later version for reading, manipulating, and writing spreadsheet files. This is done by invoking the software through "automation," a technology that facilitates the use of Excel by external software.

To help potential users of the bucking simulator and other software developed for the STUDS project determine whether their computer systems meet the requirements listed above, we developed a utility program (app. 1) that checks for the required software (fig. 8, step 2).

Simulated log bucking—
Because this study did not include a mill study (in which long logs are normally bucked into short logs at the sawmill and then converted into lumber), the process of bucking the long logs was simulated in software (fig. 8, step 3) so that data for short logs would be available for the sawing simulations. Rather than attempting to develop a sophisticated optimal bucking program like those described by Acuna and Murphy (2005) or Wang et al. (2009), we decided to use a simple simulator that follows the bucking rules used by several of the purchasers of logs from the thinning operations. This is because we wanted to emulate typical mill processing practices rather than developing an ideal solution that might not be consistent with those practices. The bucking simulator was written in the C# ("c-sharp") programming language using Microsoft Visual Studio® 2010 Professional. Appendix 2 describes the bucking rules used and also explains how sweep and crook are treated during the simulated bucking process.

Software for a Simple Bucking Simulator

Executable File (xlBuckLogs.exe)—
This file can simply be copied into any folder on the user's computer without formal installation; administrative privileges are not required. The user's computer must have Windows (XP with Service Pack 3 or any later version), Microsoft .NET Framework 4.0 or later, and Microsoft Excel 2002 or later. If those requirements are satisfied, the software will register itself with Windows the first time it is executed. Appendix 1 provides instructions on unblocking the executable file.

Supporting File (LogDataFmt.xml)—
This file, which must be present in the same folder as the executable file, defines the format of the data columns in the input long-log data worksheets and the output

short-log data worksheets. Specifications are defined for Excel columns A through AB, which are the columns used for the data worksheets. Entries in all other columns are ignored.

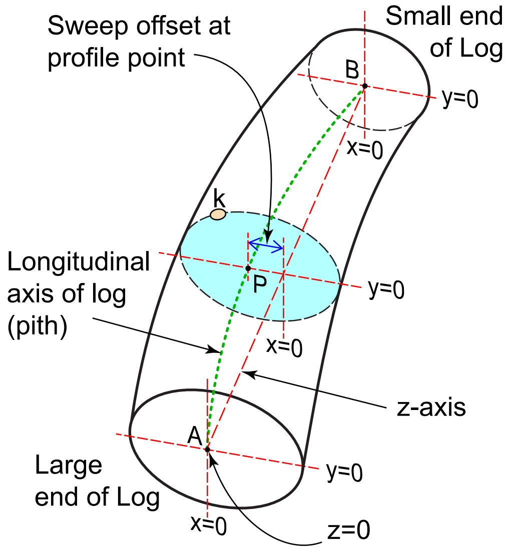
Operation—
The user navigates to the folder where the executable file has been placed and double-clicks the filename to launch the program.

Input File—
This is a Microsoft Excel spreadsheet file with a filename extension of either XLS (2002 or 2003) or XLSX (2007 or later). The file must contain one or more long-log data worksheets that conform to the format described in LogDataFmt.xml. If the file contains other worksheets as well, they are simply ignored by the software. Each long-log data worksheet must be named in the format Aw-xxxx-y; where A = a single letter representing the site (for this study, C is Cataract, W is Wildcat, and Y is Yachats); w = a single digit signifying the treatment (for this study, 2 represents the light-thinning treatment T100 and 3 represents the moderate-thinning treatment T60); xxxx = a four-digit tree number; and y = a single digit representing the index of the long log cut from the tree, where y = 1 for the butt log, 2 for the log immediately above the butt log, and 3 for the upper log.

Output File—
This is a Microsoft Excel spreadsheet file containing one worksheet for each short log bucked from the long logs described in the input file. The user enters a name for this file through the user interface of the simulator. Depending on the version installed on the user's computer, the output file must have a filename extension of either XLS or XLSX. The short-log worksheets in the output file have the format specified in the LogDataFmt.xml file. Worksheet names are the same as for the input file but with "-z" appended to the name, where z is an index number for the short log. The simulator assigns a value of 1 for the first short log bucked from the large end of the long log, assigns a value of 2 for the next short log bucked from the same long log, and continues the numbering system for middle and upper long logs. As an example, long log C2-1009-2 might be bucked into three short logs: C2-1009-2-1, C2-1009-2-2, and C2-1009-2-3. The output file would then contain three worksheets with these names. If a long log is shorter than the maximum short-log length plus maximum trim allowance (a total of 21.0 feet for this study), it is not bucked by the simulator and all of its data are transferred to the output file intact. The worksheet in the output file is then given the same name as the input long-log worksheet but with "-1" appended.

Running the Sawing Simulator

Sawing simulators require detailed information on the shape and dimensions of each log, surface-defect locations and sizes, sweep, and other characteristics that could influence the quantity and grade of lumber produced from the log. The three-dimensional system used by AUTOSAW to model logs is shown in figure 9. The details of data preparation and simulation processing with AUTOSAW (or any other simulator) are specific to that particular simulator and would not be relevant for a user who has selected another product for running simulations; however, these details are available in appendix 3, which describes the input data and the outputs resulting from sawing simulations, the software we developed to convert log-measurement data into the format required by AUTOSAW, and the software used to convert output files from the simulator into Microsoft Excel spreadsheets for analysis.



z-axis	A straight line connecting the geometric centers of the two ends of the log.
x-axis	A horizontal line extending through the z-axis and to the perimeter at each end of the log and at any profile point in the log.
y-axis	A vertical line extending through the z-axis and perpendicular to the x-axis.
Longitudinal axis	A line (curved unless the log is straight) that follows the pith from one end of the log to the other.
A and B	Reference points at the geometric centers (pith) of the two ends of the log.
k	A knot on the surface of the log.
P	The profile point associated with knot k.

Figure 9—The three-dimensional coordinate system used by AUTOSAW to describe logs to be processed by simulated sawing; note that (1) this log sweeps to the left as viewed from the large end of the log so the longitudinal axis is offset from the z-axis (in a log with no sweep the axes would be identical), and (2) the x-coordinate of profile point P is negative because of the sweep.

Analyzing Simulation Outputs

Three-Dimensional Stem Profile and Defect Data

One objective of this study was to develop a dataset that provides three-dimensional coordinates of stem profiles, branch locations as indicated by surface knots, and surface defects on the stem of each sample tree as it stood before felling. Anticipating that such data could be useful in further studies—not only for wood-quality research but also for any research requiring detailed data on stem form and branch locations (such as studies on the development of crown models)—we wrote a computer program in the Microsoft C# language that uses information recorded in the long-log data worksheets to calculate three-dimensional coordinates for each profile point and surface defect within each tree (fig. 8, step 7).

To convert data from the long-log worksheets into a three-dimensional stem-coordinate dataset for the sample trees, we mapped the three-dimensional log coordinates, which were arbitrarily established when each log was measured, into a fixed coordinate system that reflects the position of the tree stem as it stood before the tree was felled (app. 4). The mapping was somewhat more complicated than it might at first seem because the coordinate system for each log was established independently from that of every other log, including other logs from the same tree. As described above, the z-axis of the log was taken as a line segment joining the geometric center of the large end of the log with the geometric center of the small end of the log (fig. 9); the x-axis was taken as the horizontal axis and the y-axis was taken as the vertical axis, both drawn through the geometric center of the large end of the log as it lay in the initial measurement orientation. These axes were arbitrary but convenient because they were consistent with the coordinate system required by AUTOSAW for describing profile points and the locations of surface knots. However, mapping these log-based coordinates to an equivalent system of coordinates for the standing tree required a rather elaborate methodology (app. 4).

Sample Trees Felled and Long Logs Produced

The 66 selected sample trees shown in table 2 were felled and bucked into long logs at the felling site, with 185 logs produced (table 3). Most sample trees produced three long logs but 14 trees produced only two logs and one produced four logs. The number of logs produced from a given tree results from decisions by the logger and depends on the length of the tree bole and its characteristics after felling. One log that broke during yarding was discarded because it was shorter than the minimum merchantable length of 8 feet. Originally 17 feet long, it was the third log from a three-log tree, Y2-1603. Five logs were lost altogether; they may have been broken during yarding or the tags may have come off, rendering them unidentifiable. The lost logs represent 2.7 percent of the sample. In the planning stage of the study, several extra sample trees had been selected on the assumption that about 5 percent of logs would be lost. The five lost logs were all top logs with small-end diameters less than 4 inches; one was the fourth log from the only four-log tree (Y3-2062) and the others were all third logs from three-log trees (C3-2146, W3-2732, Y3-1016, and Y3-2733).

Table 3—Long logs produced from sample trees in Douglas-fir stands on the Oregon Coast Range 15 years after commercial thinning treatments, summarized by site and treatment

	Sample trees felled, classified by the number of logs produced per tree							
Grouping[a]	Two logs	Three logs	Four logs	All sample trees felled	Logs produced	Logs broken and discarded	Sample logs lost	Sample logs measured
Study site								
Cataract	2	18	0	20	58	0	1	57
Wildcat	8	11	0	19	49	0	1	48
Yachats	4	22	1	27	78	1	3	74
Treatment								
Light (T100)[b]	11	31	0	42	115	1	1	113
Moderate (T60)[c]	3	20	1	24	70	0	4	66
All sample trees	14	51	1	66	185	1	5	179

[a] The entries in the table include one log (Y2-1659-2) that was recorded at the felling site as the top log from a two-log tree. With a length of 45.8 feet, it was the longest log produced from any of the sample trees. The log broke during yarding and was re-bucked at the landing into two merchantable logs with lengths of 33.0 and 9.0 feet. In this table the two resulting logs have been shown as if they had been produced at the felling site and the tree has been reclassified as a three-log tree.

[b] Stand reduced to approximately 100 trees per acre (light thinning).

[c] Stand reduced to approximately 60 trees per acre (moderate thinning).

Table 3 summarizes tree and log counts not only by site but also by treatment. We used these categories throughout the analysis in an effort to identify variables that influence wood-quality characteristics. The two treatments (T100 = light thinning, T60 = moderate thinning) were both represented on all three sites, but more trees were removed from treatment T100 plots to reduce the higher density resulting from the lighter phase 1 thinning treatment. Although the treatment plots had been subdivided into subplots that were underplanted following the phase 1 thinnings and those that were not, a preliminary analysis with underplanting as a classification variable showed no detectable effect on the wood-quality variables. This was expected because underplanting at that stage would be unlikely to have had any effect on wood quality.

Aspect—

In wood quality studies, aspect is commonly considered a potentially important variable because it can influence the size and character of limbs and thus the knots that become embedded in lumber. Because of the layout of the STUDS study sites, however, aspect was confounded within the site and had a sharply reduced sample size. Only the Wildcat site had south-facing slopes; that entire site faces toward the southwest (fig. 3). Trees on the Cataract and Yachats sites were on slopes that faced generally northward, with aspects varying from northwest to northeast (fig. 2). As a result, the analysis described in this report did not consider aspect as an independent variable.

Competitive status of individual trees—
Although it has not often been considered in wood-quality studies, within-plot variation in the competitive status of individual trees can also influence knot distribution and knot size. We did not attempt to evaluate competition between the sample trees and their neighbors in this study but this could be an important factor to consider in future analytical efforts.

Effects of Treatment on Stem Growth (Long Logs)

Measurement Data

Table 4 summarizes basic data for the 179 long logs that were produced from the 66 sample trees and measured after yarding. It also summarizes the measurements by the position of each log within the tree; for the 77 percent of sample trees that had three logs, the butt log corresponded to the first log cut from the tree, the middle log corresponded to the second log, and the upper log corresponded to the third log. The 21 percent with only two logs were recorded as having no middle log—only a butt log and an upper log—primarily to associate the upper log designation to the part of the tree with a live crown. Although one tree had four logs when it was felled, the fourth log was lost during yarding and thus was not measured; our analyses treated the third log from that tree as an upper log.

Results of statistical analyses on the long-log data are presented in table 5. The interaction tests were run using PROC GLIMMIX in SAS version 9.4 (2013). Fixed effects tested for each response variable were treatment, adjusted DBH, log position within the tree stem (butt, middle, or upper), and two-factor interactions among the variables. Because we found that DBH was influenced by the phase 1 thinning treatments (table 1), DBH was adjusted for this analysis to accommodate different ranges for each treatment as described in Milliken and Johnson (2002). And because not all sample trees from each treatment had the same number of long logs, unique ranges were required for each treatment and long-log position. All trees had one butt log and one upper log; 77 percent had a single middle log, 21 percent had no middle log, and a single tree had two middle logs (table 3). Trees that had middle logs tended to have larger DBH than those that did not. The adjusted DBH used in the analysis for a particular log position within a tree (for example, tree *x* and log position *y*) from a particular treatment was calculated by reducing the observed DBH for tree *x* by the least-squares mean DBH for all trees from that treatment that had a long log in position *y*.

Table 4—Long logs produced from sample trees in Douglas-fir stands on the Oregon Coast Range 15 years after commercial thinning treatments, summarized by site, treatment, and log position within the tree; does not include data on one broken and discarded log or five lost logs.

		Large-end diameter		Small-end diameter		Length		Gross log volume	
Groupings for long logs measured	**Logs**	**Mean**	**Range**	**Mean**	**Range**	**Mean**	**Range**	**Mean**	**Range**
		- - - Inches - - -		*- - - Inches - - -*		*- - - - Feet - - - -*		*- - Cubic feet - -*	
Study site:									
Cataract	57	13.35	6.5–25.7	9.53	3.1–18.2	30.37	9.0–43.0	22.57	2.3–69.6
Wildcat	48	13.68	6.5–26.1	8.42	3.0–17.1	31.68	15.9–39.0	23.10	3.2–79.4
Yachats	74	14.64	6.6–25.8	10.04	3.4–19.1	31.24	9.0–39.1	28.26	2.8–87.0
Treatment:									
Light (T100)[a]	113	13.44	6.5–25.8	9.08	3.0–18.2	30.86	9.0–43.0	23.05	2.3–78.9
Moderate (T60)[b]	66	14.89	6.9–26.1	10.06	3.0–19.1	31.45	15.9–41.0	28.51	3.3–87.0
Log position:									
Butt	66	18.18	8.7–26.1	12.68	6.4–19.1	36.58	21.0–41.0	41.38	4.6–87.0
Middle	47	13.66	8.6–18.3	9.96	6.9–13.7	32.51	16.9–37.2	24.86	5.5–48.2
Upper	66	9.99	6.5–16.8	5.85	3.0–11.2	24.55	9.0–43.0	8.90	2.3–36.9
All measured logs	179	13.97	6.5–26.1	9.45	3.0–19.1	31.08	9.0–43.0	25.06	2.3–87.0

[a] Stand reduced to approximately 100 trees per acre (light thinning).
[b] Stand reduced to approximately 60 trees per acre (moderate thinning).

Random effects tested included study site (Cataract, Wildcat, or Yachats), site by treatment, site by position, site by treatment by position, and tree (table 5). Estimated components of variance associated with each of the random effects that are different from zero are represented in the table as $\hat{\sigma}_i^2$, where i is a label indicating the random effect (such as site or treatment), and the residual error estimate is represented by $\hat{\sigma}_\varepsilon^2$. The contribution of each random effect to model variation was calculated using a likelihood ratio test for a zero-variance component (in PROC GLIMMIX using the COVTEST statements), with estimates that were larger than zero presented in table 5. Because DBH had been used to stratify the sample, it was included in the analysis as a covariate to examine effects at the adjusted DBH values. The model for log-length accommodated heterogeneous behavior in the residuals that were associated with log position, which was evaluated with a test of homogeneity (SAS 9.4 PROC GLIMMIX using the COVTEST statement with HOMOGENEITY option).

Log position, either directly or through interaction effects, was strongly significant in characterizing the relationships among the responses in all tests. This was expected because logs higher in the tree are generally smaller and shorter than those nearer the ground. As can be seen in table 4, log diameters and volumes tended to be larger in plots treated with the heavier phase 1 thinning (treatment T60) than those treated with the lighter thinning (treatment T100). This is the result

Table 5—Results of tests for significant effects of treatment and log position on dimension and volume in long logs produced from sample trees in Douglas-fir stands on the Oregon Coast Range 15 years after commercial thinning treatments; mixed-effect models were fit to account for nesting, with significant random effects estimated for site, tree within site and treatment—other random effects were not significant based on likelihood ratio χ2 tests (SAS 9.4 PROC GLIMMIX COVTEST option)

Response variable (179 logs)	Effect[a]	Degrees of freedom[b]	*F* value	*p* value[c]
Long-log large-end diameter (inches)	Treatment	1,2	53.45	0.0182*
	Position	2,8	1036.39	< 0.0001*
	Treatment × position	2,8	5.55	0.0308*
	Adjusted DBH	1,99	590.21	< 0.0001*
	Position × adjusted DBH	2,99	86.95	< 0.0001*
	$\hat{\sigma}^2_{tree}=0.34$ ($p = 0.0067$), $\hat{\sigma}^2_{\varepsilon} = 1.00$			
Long-log small-end diameter (inches)	Treatment	1,2	26.26	0.0360*
	Position	2,8	708.80	< 0.0001*
	Treatment × position	2,8	8.07	0.0120*
	Adjusted DBH	1,99	246.65	< 0.0001*
	Position × adjusted DBH	2,99	42.54	< 0.0001*
	$\hat{\sigma}^2_{site} = 0.51$ ($p = 0.0424$), $\hat{\sigma}^2_{tree} = 0.45$ ($p = 0.0006$), $\hat{\sigma}^2_{\varepsilon} = 1.05$			
Long-log length (feet)	Treatment	1,2	0.36	0.6108
	Position	2,8	69.80	< 0.0001*
	Treatment × position	2,8	0.18	0.8347
	Adjusted DBH	1,99	0.56	0.4559
	Position × adjusted DBH	2,99	7.53	0.0009*
	$\hat{\sigma}^2_{site,\text{treatment},\text{position}} = 0.05$ ($p = 0.8897$), $\hat{\alpha}^2_{tree} = 1.77$ ($p = 0.3568$), $(\hat{\sigma}^2_{\varepsilon,\text{butt}},\hat{\sigma}^2_{\varepsilon,\text{middle}},\hat{\sigma}^2_{\varepsilon,\text{upper}}) = (4.61,26.95,61.70)$ ($p < 0.0001$)			
Gross long-log volume (cubic feet)	Treatment	1,2	33.35	0.0287*
	Position	2,8	700.34	< 0.0001*
	Treatment × Position	2,8	11.47	0.0045*
	Adjusted DBH	1,99	363.15	< 0.0001*
	Position × Adj-DBH	2,99	193.52	< 0.0001*
	$\hat{\sigma}^2_{site} = 0.97$ ($p = 0.3959$), $\hat{\sigma}^2_{site,\text{treatment},\text{position}} = 0.27$ ($p = 0.8791$), $\hat{\sigma}^2_{tree} = 7.92$ ($p = 0.0044$), $\hat{\sigma}^2_{\varepsilon} = 20.69$			

F value = the numerical value of the *F*-statistic used to test significance in the analysis of variance.

$\hat{\sigma}^2_i$= the estimated variance of random-effect variable *i*; (multiple indexes separated by commas indicate interaction effects); when $i = \varepsilon$, the variance estimate is for the error term or components of the error term.

DBH = diameter at breast height.

[a] The tests were carried out with adjustments for DBH assuming different ranges for the groups (Milliken and Johnson, 2002). Without DBH adjustments, only position was significant in each model (all others have $p > 0.10$).

[b] The conservative containment approach was used for degrees of freedom (this is based on split-plot type designs with restricted randomizations); if the less conservative Kenward-Roger approach (Littell et al. 2006) had been used, all tests would have had similar declarations of significance.

[c] An asterisk indicates statistically significant results ($p < 0.05$). When interactions are significant, probability values for main effects are only given for completeness.

that would be expected from such treatments, as heavier thinnings tend to produce trees with larger diameters and volumes. When adjusted DBH was included as a covariate, the interaction between treatment and log position was highly significant for both log diameters and for gross volume. Although not typically a statistically significant contributor, site appeared to contribute to the variation in long-log small-end diameter, length, and gross log volume for this study.

Sweep and Crook in Long Logs

Table 6 summarizes data on the sample logs that were recorded as having sweep or crook. Of the 179 long logs measured, 38 butt logs (21 percent) had sweep. Slightly more than half were from the Yachats site, the source for 41 percent of all sample logs; 63 percent were from the lighter phase 1 thinning (treatment T100), which also accounted for 63 percent of the sample logs.

Response variables tested in a statistical analysis of sweep—again using mixed-effects procedures in SAS (2013)—were sweep offset and the distance from the large end of the log to the center of sweep (fig. 7). The variation in sweep offset shown in table 6, combined with minimal variation in the distance from the large end of the log to the center of sweep, resulted in no statistically significant differences. We did not test log position because all logs with sweep were butt logs. Although we found heteroscedasticity in sweep offset among the sites, we also found that the treatment effect for sweep offset was not statistically significant, and that neither site (as a random effect) nor treatment had a statistically significant effect on the distance to the center of sweep.

Only six sample logs (table 6) were recorded as having crook. One of these, the only butt log with crook (W3-2042-1), also had sweep. Two-thirds of logs with crook were from treatment T60, even though that treatment accounted for only slightly more than a third of the sample logs. We did not conduct a statistical analysis for crook because the sample (only six logs) was too small for a satisfactory test.

Effects of Treatment on Stem Growth (Short Logs)

The 179 long logs from sample trees were bucked by the simulator as described in appendix 2 into 327 short logs, of which 324 could be used for simulated lumber production; three were shorter than the minimum length of 8 feet plus trim and had to be discarded. Table 7 summarizes results from the simulated bucking operation. Most long logs were bucked into two short logs. Only one, a 43-foot second log from a two-log tree, was bucked into three short logs. About 18 percent of long logs were not bucked at all because they were already short enough for mill processing. Of these, 81 percent were top logs. Both logs from one small two-log tree (DBH 8.4

Table 6—Sweep and crook in long logs cut from sample trees in Douglas-fir stands on the Oregon Coast Range 15 years after commercial thinning treatments

Defect type	Groupings	Logs with defect	Defect offset (inches)		Distance to defect center (feet)		Length of defect (feet)[a]	
			Mean	Range	Mean	Range	Mean	Range
Sweep	Study site:							
	Cataract	9	7.91	4.1–13.5	18.50	18.5–18.5	37.03	36.9–37.2
	Wildcat	9	6.81	4.8–8.5	17.40	12.0–27.5	37.13	36.9–37.4
	Yachats	20	7.91	3.2–13.5	18.45	16.5–19.2	36.95	33.0–38.5
	Treatment							
	T100[b]	24	7.48	3.2–13.5	17.82	12.0–18.6	37.06	36.8–37.4
	T60[c]	14	7.94	5.0–13.5	18.89	16.0–27.5	36.94	33.0–38.5
	Log position							
	Butt	38	7.65	3.2–13.5	18.21	12.0–27.5	37.01	33.0–38.5
	Middle	0	—	—	—	—	—	—
	Upper	0	—	—	—	—	—	—
	All logs with sweep	38	7.65	3.2–13.5	18.21	12.0–27.5	37.01	33.0–38.5
Crook	Study site:							
	Cataract	2	4.20	3.9–4.5	12.0	3.0–21.0	5.25	4.5–6.0
	Wildcat	2	3.50	2.5–4.5	8.65	7.5–9.8	10.10	5.2–15.0
	Yachats	2	4.50	4.0–5.0	18.70	13.3–24.1	3.85	2.5–5.2
	Treatment:							
	T100[b]	2	4.20	3.9–4.5	12.00	3.0–21.0	5.25	4.5–6.0
	T60[c]	4	4.00	2.5–5.0	13.68	7.5–24.1	6.98	2.5–15.0
	Log position:							
	Butt	1	4.50	—	7.50	—	15.00	—
	Middle	4	4.35	3.9–5.0	15.35	3.0–24.1	4.55	2.5–6.0
	Upper	1	2.50	—	9.80	—	5.20	—
	All logs with crook	6	4.07	2.5–5.0	13.12	3.0–24.1	6.40	2.5–15.0

— = no results.

[a] Sweep is over the entire length of the log but crook occupies only part of the log.

[b] Stand reduced to approximately 100 trees per acre (light thinning).

[c] Stand reduced to approximately 60 trees per acre (moderate thinning).

inches, total height 65.7 feet) were too short for bucking. All other trees had at least one long log that required bucking.

Log volume and the volumes of bucking waste and trim are shown in table 7 for all short logs. Typically, waste and trim are converted into chips during the bucking process. Trim is normally removed after sawing, when the pieces of lumber are trimmed to length. Waste, which is removed before sawing, consists of excess trim (more than 1 foot for this study), bucked pieces that are too short to process (less

Table 7—Bucking summary for logs produced from sample trees in Douglas-fir stands on the Oregon Coast Range 15 years after commercial thinning treatments

Study site	Long logs	Short logs bucked	Short logs discarded	Short logs in saw list	Short-log volume (cubic feet)	Bucking waste (cubic feet)	Volume in trim (cubic feet)	Waste and trim (percent)
Cataract	57	102	0	102	1,316.8	4.3	33.1	2.8
Wildcat	48	91	3[a]	88	1,126.5	8.9	28.1	3.2
Yachats	74	134	0	134	2,124.0	6.4	51.4	2.6
All Sites	179	327	3	324	4,567.3	19.6	112.5	2.8

[a] Each was the topmost log in the tree. All had small-end diameters less than the minimum diameter of 4 inches. When each log was shortened by the bucking simulator to the point where the small-end diameter was 4 inches, the remaining length was less than the minimum length of 8 feet plus trim and therefore the entire short log had to be discarded.

than 8 feet for this study), and tapered ends of logs that are smaller than the minimum processing diameter (4 inches for this study). The Wildcat site had a somewhat higher percentage of waste and trim (table 7) because its trees were generally shorter; hence, the top cut in the trees from that site was more often at a point where the diameter of the log was too small to satisfy mill standards, requiring additional simulated bucking and shorter logs. Eleven such logs came from the Wildcat site (out of 91), compared to three logs from Cataract (out of 102) and three logs from Yachats (out of 134).

Measurement Data

Table 8 summarizes basic data on short logs after the simulated bucking, organized in the same groups as table 4 for long logs. We used a somewhat different definition of the log-position category for short logs than we used for long logs, which assumed that every tree has a single butt and single upper log, that a three-log tree has a single middle log, and that a four-log tree has two middle logs. Our definition for short logs was slightly more complex, and it differed from other recent lumber recovery studies such as Lowell et al. (2012) in several ways. First, we chose to limit the butt-log designation to a single short log from each tree. Thus, when a butt long log was bucked into short logs, only one of them—the one closest to the stump—was considered a butt short log. Additional short logs bucked from the butt long log were designated as middle or upper logs, depending on how many short logs were recovered from the tree stem. Our reasoning was that the part of the tree nearest the stump has wood-quality characteristics that differ from any other part of the tree, even the section of stem just above it. A second difference was that we opted to have at least as many upper logs as middle logs in a tree (as shown by the rows in table 9). This was done to ensure that the part of the tree with a live crown was represented primarily by upper logs.

Table 8—Short logs after simulated bucking of long logs from sample trees in Douglas-fir stands on the Oregon Coast Range 15 years after commercial thinning treatments; data are summarized by site, treatment, and log position within the tree

			Large-end diameter		Small-end diameter				Gross log volume	
Groupings	Long logs	Short logs	Mean	Range	Mean	Range	Mean	Range	Mean	Range
			- - - - - - - - - - - *Inches*	- - - - - - - - - - - -			- - - - *Feet* - - - -		- - *Cubic feet* - -	
Study site:										
Cataract	57	102	12.61	4.9–25.7	10.52	4.0–18.5	16.71	8.2–20.5	12.91	0.9–39.5
Wildcat	48	88	12.74	5.2–26.1	10.05	4.0–20.3	16.56	8.5–20.5	12.80	1.1–45.6
Yachats	74	134	13.90	6.2–25.8	11.40	4.1–20.0	17.10	8.5–20.5	15.85	1.4–43.7
Treatment:										
T100[a]	113	202	12.74	4.9–25.8	10.38	4.0–20.0	16.91	8.2–20.5	13.17	0.9–43.4
T60[b]	66	122	13.90	5.8–26.1	11.37	4.1–20.3	16.70	8.5-20.5	15.63	1.1–45.6
Log position:										
Butt	66	66	18.18	8.8–26.1	14.30	6.4–20.3	18.43	12.5–20.5	23.18	4.6–45.6
Middle	47	110	14.14	7.7–20.3	12.59	6.4–18.2	17.81	12.5–20.5	17.48	3.8–35.5
Upper	66	148	10.22	4.9–16.8	7.81	4.0–15.1	15.40	8.2–20.5	7.53	0.9–22.2
All logs	179	324	13.18	4.9–26.1	10.74	4.0–20.3	16.83	8.2–20.5	14.10	0.9–45.6

[a] Stand reduced to approximately 100 trees per acre (light thinning).

[b] Stand reduced to approximately 60 trees per acre (moderate thinning).

Table 9—The BMU (Butt-Middle-Upper) classification for short logs as defined over the range of short logs cut from sample trees in Douglas-fir stands on the Oregon Coast Range 15 years after commercial thinning treatments

Total short logs cut from the tree	Position of the short log within the tree stem					
	1	2	3	4	5	6
2	B	U				
3	B	M	U			
4	B	M	U	U		
5	B	M	M	U	U	
6	B	M	M	U	U	U

As with long logs, we tested the short-log data for significant fixed effects by using the mixed-effects procedure in SAS (2013). The results are presented in table 10. For this analysis DBH was adjusted in a similar way as in table 5 to account for the fact that not all sample trees from a particular treatment had the same number of middle and upper logs (table 9). Trees with more logs (and therefore typically more total stem length) tended to have larger DBH.

Table 10—Results of tests for significant effects of treatment and log position on dimensions and volumes of short logs produced from sample trees in Douglas-fir stands on the Oregon Coast Range 15 years after commercial thinning treatments

Response variable (324 logs)	Effect[a]	Degrees of freedom[b]	F value	p value[c]
Short-log large-end diameter (inches)	Treatment	1,2	87.09	0.0113*
	Position	2,8	1086.86	< 0.0001*
	Treatment × position	2,8	8.98	0.0090*
	Adjusted DBH	1,244	1440.95	< 0.0001*
	Position × adjusted DBH	2,244	65.75	< 0.0001*
	$\hat{\sigma}^2_{site,treatment} = 0.01$ ($p = 0.6888$), $\hat{\sigma}^2_{tree} = 0.06$ ($p = 0.3346$), $(\hat{\sigma}^2_{\varepsilon,butt}, \hat{\sigma}^2_{\varepsilon,middle}, \hat{\sigma}^2_{\varepsilon,upper}) = (0.51, 1.06, 3.58)$ ($p < 0.0001$)			
Short-log small-end diameter (inches)	Treatment	1,2	23.39	0.0402*
	Position	2,8	771.43	< 0.0001*
	Treatment × position	2,8	9.30	0.0082*
	Adjusted DBH	1,244	787.62	< 0.0001*
	Position × adjusted DBH	2,244	45.69	< 0.0001*
	$\hat{\sigma}^2_{site} = 0.01$ ($p = 0.8820$), $\hat{\sigma}^2_{site,treatment} = 0.08$ ($p = 0.1671$) $\hat{\sigma}^2_{tree} = 0.18$ ($p = 0.0002$), $(\hat{\sigma}^2_{\varepsilon,butt}, \hat{\sigma}^2_{\varepsilon,middle}, \hat{\sigma}^2_{\varepsilon,upper}) = (0.12, 0.89, 4.19)$ ($p < 0.0001$)			
Short-log length (feet)	Treatment	1,2	0.65	0.5053
	Position	2,8	74.61	< 0.0001*
	Treatment × position	2,8	0.02	0.9797
	Adjusted DBH	1,244	3.26	0.0721
	Position × adjusted DBH	2,244	2.46	0.0878
	$\hat{\sigma}^2_{tree} = 0.22$ ($p = 0.0257$), $(\hat{\sigma}^2_{\varepsilon,butt}, \hat{\sigma}^2_{\varepsilon,middle}, \hat{\sigma}^2_{\varepsilon,upper}) = (0.60, 1.29, 7.40)$ ($p < 0.0001$)			
Gross short-log volume (cubic feet)	Treatment	1,2	59.19	0.0165*
	Position	2,8	731.93	< 0.0001*
	Treatment × position	2,8	12.85	0.0032*
	Adjusted DBH	1,244	737.95	< 0.0001*
	Position × adjusted DBH	2,244	144.68	< 0.0001*
	$\hat{\sigma}^2_{site} = 0.24$ ($p = 0.4603$), $\hat{\sigma}^2_{tree} = 1.53$ ($p = 0.0052$), $\hat{\sigma}^2_{site,\mathrm{treatment,position}} = 0.003$ ($p = 0.9917$), $(\hat{\sigma}^2_{\varepsilon,butt}, \hat{\sigma}^2_{\varepsilon,middle}, \hat{\sigma}^2_{\varepsilon,upper}) = (3.94, 10.71, 14.59)$ ($p < 0.0001$)			

DBH = diameter at breast height.

$\hat{\sigma}^2_i$=the estimated variance of random-effect variable i (multiple indexes separated by commas indicate interaction effects); when $i = \varepsilon$, the variance estimate is for the error term or components of the error term.

[a] The tests were carried out with adjustments for DBH assuming different ranges for the groups (Milliken and Johnson 2002). Without DBH adjustments, only position was significant in each model (all others have $p > 0.10$).

[b] The conservative containment approach was used for degrees of freedom (this is based on split-plot type designs with restricted randomizations); if the less conservative Kenward-Roger approach (Littell et al. 2006) had been used, all tests would have had similar declarations of significance.

[c] An asterisk indicates statistically significant results ($p < 0.05$). When interactions are significant, probability values for main effects are only given for completeness.

For the most part, the results of the analysis summarized in table 10 are similar to those for long logs (table 5). Log position in conjunction with adjusted tree DBH was strongly significant, as was the interaction of log position and treatment for large-end diameter, small-end diameter, and gross volume. Unsurprisingly, short-log length was significantly influenced by log position but not by treatment or adjusted DBH. As with long logs, site appeared to contribute to variation in large-end and small-end diameters and in gross volume for short logs.

Sweep and Crook in Short Logs

Bucking long logs into short logs invariably reduces sweep. After bucking, the 38 long logs with sweep (table 6) became 76 short logs with sweep (table 11) but severity (expressed as sweep offset) decreased from an average of 7.65 inches in long logs (equivalent 1.8 percent of log length) to an average of only 1.94 inches in short logs (equivalent on average to 0.8 percent of log length). This reduction is such that the remaining sweep is unlikely to have much effect on the lumber from the affected logs.

Bucking has different effects on crook, depending on its location, length, and severity. If bucking occurs within the crook, the effect on the short log may be less severe. Alternatively, bucking can remove a short crook altogether (a common practice in the mill yard); or it can leave the entire crook in one of the short logs. For the six incidents of crook in this study, all were positioned so that bucking had no effect on the crook, leaving the entire crook in a single short log. Rather than override the bucking algorithm to remove the crook or reduce its severity, we chose to leave it in place. This increases the likelihood of negative impacts on the lumber recovery from the six affected short logs. It also means that for all three sites and both treatments, two measures—crook offset and crook length—were the same for short logs (table 11) as they were for long logs (table 6).

Effects of Treatment on Surface Defects

Of the 11,475 profile points recorded for the 179 sample long logs, 453 were diameter measurements (diameters measured at the large and small ends of the logs, at four feet from the large end of butt logs, and at intervals along the log when necessary to ensure that profile-point locations were no more than four feet apart). The remaining 11,022 profile points corresponded to surface defects. Most of these (10,970 profile points) were for knots, of which 4,479 (41 percent) were live knots, 44 were small surface burls, three were forked tops, and five were surface scars (two of which had some decay). For the simulated sawing, forked tops were treated as large knots and the burls and scars were judged to penetrate the bole only a short distance and therefore be removed with the slab when the log was squared up for

Table 11—Sweep and crook in the sample short logs cut from sample trees in Douglas-fir stands on the Oregon Coast Range 15 years after commercial thinning treatments

Defect type	Groupings	Logs with defect	Defect offset Mean	Defect offset Range	Distance to defect center Mean	Distance to defect center Range	Length of defect Mean	Length of defect Range
			Inches	*Inches*	*Feet*	*Feet*	*Feet*	*Feet*
Sweep	Study site:							
	Cataract	18	1.96	1.0–3.4	9.84	9.8–9.9	18.49	18.5–18.5
	Wildcat	18	1.90	0.7–5.0	9.66	8.2–11.5	18.49	18.5–18.5
	Yachats	40	1.95	0.8–3.3	9.72	8.2–9.9	18.39	16.5–20.5
	Treatment:							
	T100[a]	48	1.89	0.7–3.8	9.74	8.2–9.9	18.49	18.4–18.5
	T60[b]	28	2.02	1.0–5.0	9.73	8.2–11.5	18.35	16.5–20.5
	Log position:							
	Butt	38	2.00	0.8–3.8	9.66	8.2–9.8	18.49	16.5–20.5
	Middle	38	1.89	0.7–5.0	9.81	8.2–11.5	18.39	16.5–18.5
	Upper	0	—	—	—	—	—	—
	All logs with sweep	76	1.94	0.7–5.0	9.73	8.2–11.5	18.44	16.5–20.5
Crook	Study site:							
	Cataract	2	4.20	3.9–4.5	3.75	3.0–4.5	5.25	4.5–6.0
	Wildcat	2	3.50	2.5–4.5	8.65	7.5–9.8	10.10	5.2–15.0
	Yachats	2	4.50	4.0–5.0	9.45	5.6–13.3	3.85	2.5–5.2
	Treatment:							
	T100a	2	4.20	3.9–4.5	3.75	3.0–4.5	5.25	4.5–6.0
	T60b	4	4.00	2.5–5.0	9.05	5.6–13.3	6.98	2.5–15.0
	Log position:							
	Butt	1	4.50	—	7.50	—	15.00	—
	Middle	1	3.90	—	3.00	—	4.50	—
	Upper	4	4.00	2.5–5.0	8.30	4.5–13.3	4.73	2.5–6.0
	All logs with crook	6	4.07	2.5–5.0	7.28	3.0–13.3	6.40	2.5–15.0

— = no results.

[a] Stand reduced to approximately 100 trees per acre (light thinning).

[b] Stand reduced to approximately 60 trees per acre (moderate thinning).

sawing. This left only the knots and forked tops with the potential to influence wood quality in our analysis.

Surface Knots

The size, frequency, and distribution of knots can affect the quality of lumber, while also serving as indicators of successful habitat improvement for species that depend on large branches. To understand the factors that could influence these characteristics, we studied the size and density of surface knots at three levels of disaggregation: the entire merchandized tree stem, long logs, and short logs. We anticipate that this information will be valuable to foresters who are designing operations for both forest products and habitat improvement and want to know how the size and density of knots (indicating branches) on the standing tree would be affected by treatments or site variables. Loggers are interested in both trees and long logs because trees are what they buy and long logs are what they produce and sell. Forest products companies are interested in both long logs and short logs because long logs are what they buy and short logs are what they process into lumber or other products.

We used regression analysis to identify the factors that influence knot size and density in tree stems and logs and to quantify those effects in a way that would be useful to foresters, loggers, and forest products specialists. As response variables we identified two measures that are of general interest in wood-quality studies: knot diameter and knot density. Then at each level of disaggregation (tree stems, long logs, and short logs) we conducted a regression analysis for each response variable using SAS (2013). The fixed-effect model to which the data were fitted with regression analysis was:

$$E(Y)=\beta_0+\beta_1 D+\beta_2 LF+\beta_3 L+\beta_4 E+\beta_5 T+\beta_6 B+\beta_7 U+\beta_8(D*B)+\beta_9(D*U) \qquad (1)$$

where:

Y = the response variable (inverse mean diameter of surface knots or mean density of surface knots within tree stems, long logs, or short logs),

β_j = parameters estimated via linear regression, j = 0 through 9,

D = an appropriate function of diameter, in inches (DBH, 1/DBH, or $\sqrt{DBH}$ for tree stems, small-end diameter—SED, 1/SED, or $\sqrt{SED}$—for long logs and short logs),

LF = live-knot fraction (live knots divided by total surface knots recorded in each merchandized tree stem, long log, or short log),

L = length of the merchandized portion of the tree stem or length of the log, in feet,

E = ground elevation at the base of the tree, in feet above mean sea level,

T = a dummy variable for treatment (T = 0 for trees from treatment T100 and T = 1 for trees from treatment T60),

B = for logs only, a dummy variable for log position (B = 1 for butt logs, B = 0 otherwise),

U = for logs only, a dummy variable for log position (U = 1 for upper logs, U = 0 for middle and upper logs),

$D*B$ = for logs only, the log diameter or its transformation (D) multiplied by the dummy variable for butt logs (B),

$D*U$ = for logs only, the log diameter or its transformation (D) multiplied by the dummy variable for upper logs (U).

We used small-end diameter as a variable in the analysis of logs because it is the measure most often used in research on lumber recovery. Large-end and small-end log diameters were highly correlated ($\rho = 0.95$ for long logs, $\rho = 0.96$ for short logs), so only one of the two could be used as an independent variable in regression analysis.

To some extent the live-knot fraction is related to log position because the logs from the section of the stem where the live crown is located have larger live-knot fractions and also come from the middle-to-upper portion of the tree. However, our tests suggested that the relationship between the butt-middle-upper log position and the live-knot fraction varied among the sample trees; we therefore included both as potential independent variables. Because it is a categorical variable, we represented the butt-middle-upper variable by two dummy variables: one for butt logs and the other for upper logs, both of which were present in all sample trees. An additional variable was not needed for middle logs because by definition they are those for which $B = U = 0$.

To capture variation resulting from the hierarchical structure of the experiment, we included random effects for site and site by treatment in initial models, and random effects for tree and tree by log position for long and short logs. For each model, a full fixed and random effect model was initially fit. The random effect structure was then determined by sequential chi-square tests for variance components equal to zero, and random effects that were not significant were dropped (SAS 9.4 PROC GLIMMIX, COVTEST statements). In some instances, fitting heterogeneous residuals based on log position (butt, middle, upper) improved the model characteristics. After the full model was fitted, the fixed-effect model was determined through a backward elimination procedure employing the usual t-tests—a process that is typically followed for determination of mixed-effect models when modeling longitudinal data (Cheng et al. 2010). For these regression models, we estimated degrees of freedom using the Kenward-Roger approach (Littell et al. 2006).

Knots in tree stems—

Table 12 summarizes data on surface knots by site, by treatment, and for all sample trees in the study combined. Mean values for several tree-related variables that are commonly of interest to foresters (DBH, stem length, and tree elevation) are also shown in the table. Merchandized stem length, which was used to calculate knot density in knots per foot of merchandized stem, is the sum of the lengths of the long logs cut from the tree, excluding any unmerchantable stem sections that were bucked out and excluding the one broken and discarded log and the five lost logs whose surface knots could not be measured (table 3).

Table 12—Number, size and density of surface knots in the merchandized stems of sample trees in Douglas-fir stands on the Oregon Coast Range 15 years after commercial thinning treatments

					Knots per tree		Knot diameter		Knots per foot of merchandized stem	
Groupings	Number of trees	Mean DBH	Mean merchandized stem length	Mean tree elevation	Total	Live percent	Mean	Range	Mean	Range
		Inches	*Feet*	*Feet*			*- - - Inches - - -*			
Study sites										
Cataract	20	16.59	86.55	676	152.9	32.6	0.92	0.73–1.30	1.760	0.950–2.227
Wildcat	19	17.13	80.02	1034	183.2	43.9	1.00	0.69–1.37	2.281	1.269–3.349
Yachats	27	18.29	85.61	740	164.1	44.1	1.16	0.73–1.82	1.907	1.300–2.783
Treatment										
T100[a]	42	16.64	83.03	804	159.8	39.2	1.00	0.69–1.82	1.909	1.269–3.070
T60[b]	24	18.85	86.48	807	177.4	43.3	1.10	0.82–1.72	2.076	0.950–3.349
All sample trees	66	17.44	84.28	805	166.2	40.9	1.04	0.69–1.82	1.970	0.950–3.349

DBH = diameter at breast height.

[a] Stand reduced to approximately 100 trees per acre (light thinning).

[b] Stand reduced to approximately 60 trees per acre (moderate thinning).

The largest knots on average were those recorded at the Yachats site, which also had the largest trees as measured by DBH and the second-largest trees (behind the Cataract site) as measured by merchandized stem length. The Wildcat site had the second-largest average knot size even though its trees were shorter than either of the other two sites; mean DBH at Wildcat, however, was midway between the others. Wildcat also had the largest number of knots per tree and the highest overall knot density. Trees from treatment T60 plots had more knots per tree, larger mean knot diameters, and more knots per foot of merchandized stem than trees from treatment T100 plots.

Knots in long logs—

Table 13 summarizes data on surface knots by site, by treatment, and for all logs combined; each major group is further subdivided by the position of the log within the tree stem. Although forked tops for this study were treated as large surface knots for the simulated sawing, they are not included here because they are not a potential consequence of either treatment T60 or treatment T100—often resulting instead from breakage of the upper stem, with two or more branches subsequently forming the new forked top. If both tops become full boles, a pronounced crotch can develop and one or more logs can be recovered from each top. The three forked tops observed in sample trees in this study were small, with only one top from each tree producing a usable log. The sample size of three forked tops was too small to permit a separate statistical analysis.

Table 13—Surface knots in long logs measured after yarding from sample trees in Douglas-fir stands on the Oregon Coast Range 15 years after commercial thinning treatments; T100 is a light thinning to approximately 100 residual trees per acre, and T60 is a moderate thinning to approximately 60 residual trees per acre

				Knots per log		Knot diameter		Knots per foot of log	
Groupings	Log position	Long logs	Knots	Total	Percent alive	Mean	Range	Mean	Range
						- - - Inches - - -			
Study site:									
Cataract	Butt	20	1,105	55.3	0.9	0.81[a]	0.50–4.25	1.507	0.439[g]–2.081
	Middle	17	1,061	62.4	28.7	0.90	0.50–3.40	1.980	1.270–2.961
	Upper	20	892	44.6	76.5	1.07	0.50–3.90	1.935	1.333–3.059
	All	57	3,058	53.6	32.6	0.93	0.50–4.25	1.798	0.439–3.059
Wildcat	Butt	19	1,389	73.1	2.9	0.84	0.50–3.00	1.975	0.729–3.414
	Middle	10	732	73.2	59.3	1.25	0.50–4.55	2.397	1.059–3.303
	Upper	19	1,360	71.6	77.7	1.05	0.50–6.25	2.604[f]	1.690–3.519[h]
	All	48	3,481	72.5	44.0	1.01	0.50–6.25	2.312	0.729–3.519
Yachats	Butt	27	1,410	52.2	6.9	0.91	0.50–2.60	1.434[e]	0.649–2.168
	Middle	20	1,519	76.0	48.0	1.31	0.50–9.20[d]	2.224	1.270–3.346
	Upper	27	1,502	55.6	75.2	1.31[b]	0.45[c]–7.90	2.436	1.386–3.216
	All	74	4,431	59.9	44.1	1.16	0.45–9.20	2.013	0.649–3.346
Treatment:									
T100	Butt	42	2,466	58.7	3.7	0.84[a]	0.50–4.25	1.600[e]	0.699–2.818
	Middle	29	2,056	70.9	42.7	1.11	0.50–5.35	2.168	1.059–3.303
	Upper	42	2,190	52.1	76.0	1.13	0.50–7.40	2.215	1.333–3.519[h]
	All	113	6,712	59.4	39.2	1.02	0.50–7.40	1.975	0.699–3.519
T60	Butt	24	1,438	59.9	3.8	0.89	0.50–3.00	1.631	0.439[g]–3.414
	Middle	18	1,256	69.8	46.8	1.21	0.50–9.20[d]	2.180	1.270–3.346
	Upper	24	1,564	65.2	76.8	1.22[b]	0.45[c]–7.90	2.538[f]	1.462–3.462
	All	66	4,258	64.5	43.4	1.10	0.45–9.20	2.111	0.439–3.462
All measured logs:									
	Butt	66	3,904	59.1	3.7	0.86[a]	0.50–4.25	1.612[e]	0.439[g]–3.414
	Middle	47	3,312	70.5	44.3	1.15	0.50–9.20[d]	2.172	1.059–3.346
	Upper	66	3,754	56.9	76.3	1.16[b]	0.45[c]–7.90	2.333[f]	1.333–3.519[h]
	All	179	10,970	61.3	40.8	1.05	0.45–9.20	2.025	0.439–3.519

[a] Smallest mean value for knot diameter.

[b] Largest mean value for knot diameter.

[c] Smallest individual value for knot diameter.

[d] Largest individual value for knot diameter.

[e] Smallest mean value for knots per foot of long log.

[f] Largest mean value for knots per foot of long log.

[g] Smallest individual value of knots per foot of long log.

[h] Largest individual value of knots per foot of long log.

On average, logs from higher in the tree stem had larger knots than logs from lower in the tree (table 13). The smallest mean knot diameters within the major groups were measured in butt logs from the Cataract site, treatment T100, and the south-facing slopes at the Wildcat site. The largest mean knot diameters occurred in upper logs at the Yachats site and in treatment T60. The smallest individual knot diameter was almost always 0.5 inches, the minimum diameter for measurement in this study; the exception was one knot that measured 0.4 x 0.5 inches for an average diameter of 0.45 inches. The largest knot (9.2 inches) was measured on the Yachats site. It was in the middle of a three-log tree from treatment T60.

Knot density is shown in table 13 as the number of surface knots per foot of log. Within each major group, the smallest average knot density occurred in butt logs and the largest occurred in upper logs, which typically represent the part of the tree with a living crown. The same result holds for the smallest and largest individual knot densities, although the locations of these extreme values did always track with the locations of average values; for instance, the smallest individual knot density at any site occurred in a log from the Cataract site, but the smallest average density on any site was from the Yachats site. For the treatment groups, the smallest average density occurred in butt logs from treatment T100 but the smallest individual density occurred in a log from treatment T60; and the largest average density occurred in upper logs from treatment T60 but the largest individual density was in an upper log from treatment T100. Overall, logs from the Wildcat site (and thus from south-facing slopes) had the highest average densities in all position classes as well as both the largest individual and the largest average densities measured in the study.

Knots in short logs—
Table 14 summarizes data on surface knots by site, by treatment, and for all logs combined; each major group is further subdivided by the position of the log within the tree stem. The total number of knots recorded in long logs (10,970) was reduced by 2 percent in short logs (to 10,747) because of knots that were removed, along with excess trim, from the long logs when they were bucked into short logs. The smallest and largest individual knot diameters recorded for short logs mirrored the long-log data (table 13), but not the mean knot diameters and sometimes not the site where they occurred; for instance, the smallest mean knot diameter in short logs occurred on the Wildcat site, whereas the smallest mean knot diameter in long logs was on the Cataract site. The largest mean knot diameter in both short logs and long logs occurred in the moderate thinning treatment on the Yachats site.

Table 14—Surface knots in short logs after simulated bucking of long logs from sample trees in Douglas-fir stands on the Oregon Coast Range 15 years after commercial thinning treatments; T100 is a light thinning to approximately 100 residual trees per acre, and T60 is a moderate thinning to approximately 60 residual trees per acre

				Knots per log		Knot diameter		Knots per foot of log	
Groupings	Log position	Long logs	Knots	Total	Percent alive	Mean	Range	Mean	Range
						- - - *Inches* - - -			
Study site:									
Cataract	Butt	20	424	21.2	0.0	0.76	0.50–1.90	1.159	0.195–1.946
	Middle	36	1,178	32.7	9.2	0.84	0.50–4.25	1.849	0.683–2.848
	Upper	46	1,423	30.9	59.9	1.03	0.50–3.90	2.007	1.186–3.091
	All	102	3,025	29.7	31.6	0.91	0.50–4.25	1.785	0.195–3.091
Wildcat	Butt	19	598	31.5	0.0	0.76[a]	0.50–1.90	1.706	0.162[g]–3.622
	Middle	28	1,163	41.5	16.4	0.97	0.50–4.25	2.335	0.729–3.730
	Upper	41	1,568	38.2	75.7	1.13	0.50–6.25	2.581[f]	1.030–4.080[h]
	All	88	3,329	37.8	41.3	1.00	0.50–6.25	2.314	0.162–4.080
Yachats	Butt	27	577	21.4	4.2	0.83	0.50–1.90	1.149[e]	0.324–2.005
	Middle	46	1,555	33.8	20.7	1.08	0.50–4.85	1.904	0.703–3.647
	Upper	61	2,261	37.1	69.3	1.32[b]	0.45[c]–9.20[d]	2.346	1.394–4.032
	All	134	4,393	32.8	43.6	1.14	0.50–9.20	1.953	0.324–4.032
Treatment:									
T100	Butt	42	1,040	24.8	1.6	0.78[a]	0.50-1.90	1.338	0.324–2.919
	Middle	68	2,386	35.1	16.0	0.95	0.50–4.25	1.972	0.703–3.647
	Upper	92	3,135	34.1	66.0	1.14	0.50–7.40	2.194	1.030–4.080[h]
	All	202	6,561	32.5	37.5	1.00	0.50–7.40	1.941	0.324–4.080
T60	Butt	24	559	23.3	1.3	0.79	0.50–1.90	1.267[e]	0.162[g]–3.621
	Middle	42	1,510	36.0	15.6	1.01	0.50–4.85	2.035	0.683–3.730
	Upper	56	2,117	37.8	72.5	1.23[b]	0.45[c]–9.20[d]	2.489[f]	1.294–4.032
	All	122	4,186	34.3	42.6	1.07	0.45–9.20	2.093	0.162–4.032
All measured logs:									
	Butt	66	1,599	24.2	1.7	0.79[a]	0.50-1.90	1.312[e]	0.162[g]–3.622
	Middle	110	3,896	35.4	15.8	0.97	0.50–4.85	1.996	0.683–3.730
	Upper	148	5,252	35.5	68.7	1.17[b]	0.45[c]–9.20[d]	2.306[f]	1.303–4.080[h]
	All	324	10,747	33.2	39.5	1.03	0.45–9.20	1.998	0.162–4.080

[a] Smallest mean value for knot diameter.

[b] Largest mean value for knot diameter.

[c] Smallest individual value for knot diameter.

[d] Largest individual value for knot diameter.

[e] Smallest mean value for knots per foot of long log.

[f] Largest mean value for knots per foot of long log.

[g] Smallest individual value of knots per foot of long log.

[h] Largest individual value of knots per foot of long log.

Compared to long-log data, knot densities for short logs were similar but the range of densities was narrower—0.162 to 4.080 knots per foot versus 0.439 to 3.519 knots per foot—because knots tend to clump in whorls rather than being uniformly spaced along the length of Douglas-fir stems. The knot density that results when a long log is bucked into short logs depends on where the bucking cuts are made relative to these clumps. Our bucking algorithm (app. 2) did not consider whorls or other surface features when determining the location of the bucking cuts.

As with long logs, knot density in short logs was smallest in butt logs and largest in upper logs. This held true both for mean values and for individual maximums and minimums. Some shifting of the minimum-density values occurred within the major groups, however; the smallest individual density occurred on the Cataract site (table 13) for long logs but on the Wildcat site for short logs (table 14). The smallest mean density also occurred in treatment T100 for long logs, but not for short logs. Conversely, the largest mean and individual short-log densities for short logs mirrored the long-log data: on the Wildcat site, treatment T100 (highest individual), treatment T60 (highest mean), and upper logs.

Size of Surface Knots

The mean size of knots in a tree is influenced by such factors as genetics, local growing conditions (especially stand density), and the management history of the stand. One purpose of this study was to determine whether the treatment, elevation, or other measured variables could be associated with knot size. The results of regression analyses for tree stems, long logs, and short logs (table 15) showed no significant treatment effect and no statistically significant effect of the elevation variable. However, DBH was shown to be significantly influenced by treatment (table 1) and the square root of either DBH or the closely correlated small-end log diameter was significant for all three response variables, therefore suggesting an indirect treatment effect. Site was statistically significant as a random effect for all three response variables as was tree for both long and short logs.

Knot size in tree stems—

The results of regression analysis for inverse mean knot diameter in tree stems suggested a direct relationship between knot diameter and DBH, with an adjustment for live-knot fraction. A higher proportion of live knots was associated with a larger average knot size. The equation explained about two-thirds of the variance in the data on inverse knot diameter in tree stems.

Knot size in long logs—

The results of regression analysis suggested that logs with larger diameters and a larger percentage of live knots tend to have larger knots, although the equation

Table 15—Regression analyses for the inverse mean diameter of surface knots, in inches, from sample trees in Douglas-fir stands on the Oregon Coast Range 15 years after commercial thinning treatments; overall fit values were calculated on the original scale (inches), R^2 and marginal error estimates were based on back-transformed knot diameters, and variance and error components were calculated in terms of inverse knot diameters

	Overall fit		Parameter estimates for individual variables					
Level of analysis	Statistic	Value	Regression variable	$\hat{\beta}_j$	Standard error	Degrees of freedom	t	p value
Tree stems	Adjusted R^2-*conditional*	0.751	Intercept	2.3503	0.1105	52.12	21.27	< 0.0001
	Adjusted R^2-*marginal*	0.650	D = $\sqrt{(DBH\ (inches))}$	-0.2914	0.0268	61.30	-10.87	< 0.0001
	RMSE-*marginal*	0.1441	LF = Live-knot fraction	-0.3116	0.0931	62.00	-3.40	0.0012
	Observations	66						
			$\hat{\sigma}^2_{site}$=0.004 (p=0.0010), $\hat{\sigma}^2_{\varepsilon}$=0.010					
Long logs	Adjusted R^2-*conditional*	0.737	Intercept	1.8013	0.1040	37.97	17.32	< 0.0001
	Adjusted R^2-*marginal*	0.477	D = $\sqrt{(SED\ (inches))}$	-0.2126	0.0281	129.1	-7.55	< 0.0001
	RMSE-*marginal*	0.2275	LF = Live-knot fraction	-0.4671	0.0505	171.1	-9.25	< 0.0001
	Observations	179	B*D = Butt log*$\sqrt{SED}$	0.0462	0.0098	117.6	4.70	< 0.0001
			$\hat{\sigma}^2_{site}$=0.006 (p<0.0001), $\hat{\sigma}^2_{tree}$=0.006 (p=0.0038), $\hat{\sigma}^2_{\varepsilon}$=0.017					
Short logs	Adjusted R^2-*conditional*	0.783	Intercept	1.4698	0.1291	84.72	11.38	< 0.0001
	Adjusted R^2-*marginal*	0.469	D = $\sqrt{(SED,inches)}$	-0.0889	0.0342	242.4	-2.60	0.0100
	RMSE-*marginal*	0.2350	LF = Live-knot fraction	-0.4184	0.0400	315.6	-10.46	< 0.0001
	Observations	324	U = Upper log	0.4013	0.1204	258.9	3.33	0.0010
			U*D =Upper log*$\sqrt{SED}$	-0.1485	0.0356	250.6	-4.17	< 0.0001
			B*D = Butt log*$\sqrt{SED}$	0.0458	0.0060	259.8	7.66	< 0.0001
			$\hat{\sigma}^2_{site}$= 0.006 (p = 0.0003), $\hat{\sigma}^2_{tree}$= 0.011 (p < 0.0001), $\hat{\sigma}^2_{\varepsilon}$= 0.017					

$\hat{\beta}_j$ = the estimated regression coefficient for variable j, where $j = 0$ for the regression intercept and $j > 0$ for the independent variables in the equation.

t = the "Student's" t-statistic for testing whether $\beta_j = 0$ (may be approximate).

DBH = diameter at breast height.

SED = small-end diameter of the log.

R^2 = the statistical coefficient of determination (adjusted for the number of model parameters, based on either conditional or marginal residuals as determined on the original scale).

RMSE = the square root of the mean squared error (commonly known as "root mean squared error").

$\hat{\sigma}^2_i$ = the estimated variance of random-effect variable i; when $i = \varepsilon$, the variance estimate is for the error term or components of the error term.

explained slightly less than half of the variance in the data on a marginal basis (setting random effects to zero). The combination of a negative regression coefficient for the square root of log diameter, log position, and a positive sign for the log-position variable suggested that, overall, surface knots in butt logs tend to be smaller than those found in middle or upper logs.

Knot size in short logs—
Regression analysis showed statistical significance for the square root of the diameter at the small end of the log, live-knot fraction, log position as defined in table 15 by the U variable, and adjustments for the square root of the diameter at the small end of the log for different log positions. Altogether, the regression suggested that knots tend to be larger in logs with larger small-end diameters and in logs with larger live-knot fractions (which tend to be middle and upper logs)—at any given small-end log diameter, butt logs tend to have the smallest knots and upper logs the largest, with knots in middle logs lying between the two extremes. The equation explained about half of the observed variance in the data on mean knot diameter in short logs.

Density of Surface Knots

Knot density in tree stems—
We hypothesized that knot density within the merchandized tree stem, measured in knots per foot of merchandized stem length, could be influenced by the same variables as in equation (1) for knot size. However, regression analysis (table 16) suggested that only DBH and elevation are significant predictors of mean knot density in tree stems, with the equation explaining only a little more than a third of the total variance in the data. Even so, the results suggested that knot density tends to increase with increasing DBH but is not affected by live-knot fraction or merchandized stem length. The regression relationship described both treatment groups without a simple adjustment for treatment; however, a statistical contrast evaluating how the predicted DBH values from this regression differed among treatments at a common elevation indicated significant differences (1.92 for T100 versus 2.05 for T60, p-value for difference < 0.0001). When taken together with the finding that DBH was strongly influenced by treatment (table 1), this suggested a strong, if indirect, treatment effect on knot density in tree stems.

Knot density in long logs—
Regression analysis for knot density showed no statistically significant treatment effect. However, because the effect of treatment on DBH was significant (table 1) and small-end log diameter is highly correlated with DBH, the treatment arguably had an indirect effect on knot density. Small-end log diameter, live-knot fraction, elevation, and an adjustment for small-end diameter in butt logs as defined by the

Table 16—Regression analyses for knot density—as measured in knots per foot of length—for tree stems, long logs, and short logs from sample trees in Douglas-fir stands on the Oregon Coast Range 15 years after commercial thinning treatments; variables whose parameters were not significantly different from zero at $\alpha = 0.05$ have been excluded and the equations refitted without them

	Overall fit		Parameter estimates for individual variables					
Level of analysis	Statistic	Value	Regression variable	$\hat{\beta}_j$	Standard error	Degrees of freedom	t	p value
Tree stems	Adjusted R^2-*conditional*	0.378	Intercept	-0.0608	0.3198	63	-0.19	0.8497
	Adjusted R^2-*marginal*	0.378	D = DBH (inches)	0.0541	0.0113	63	4.79	< 0.0001
	RMSE-*marginal*	0.3748	E = Elevation (feet)	0.0014	0.0003	63	4.65	< 0.0001
	Observations	66						
				$\hat{\sigma}^2_{\varepsilon} = 0.141$				
Long logs	Adjusted R^2-*conditional*	0.770	Intercept	0.4131	0.3932	63.1	1.05	0.2975
	Adjusted R^2-*marginal*	0.391	D = SED (inches)	0.0539	0.0196	101.2	2.75	0.0071
	RMSE-*marginal*	0.5146	LF = Live-knot fraction	0.8713	0.1655	152.8	5.27	< 0.0001
	Observations	179	E = Elevation (feet)	0.0012	0.0004	42.8	3.00	0.0045
			B*D = Butt log * SED	-0.0369	0.0118	31.5	-3.13	0.0037
			$\hat{\sigma}^2_{tree} = 0.108$ ($p < 0.0001$), $\hat{\sigma}^2_{position} = 0.025$ ($p = 0.0015$), $\hat{\sigma}^2_{\varepsilon} = 0.139$					
Short logs	Adjusted R^2-*conditional*	0.693	Intercept	0.9850	0.3050	53.4	3.23	0.0021
	Adjusted R^2-*marginal*	0.350	LF = Live-knot fraction	0.5648	0.0989	59.9	5.71	< 0.0001
	RMSE-*marginal*	0.5912	E = Elevation (feet)	0.0012	0.0004	54.9	3.16	0.0025
	Observations	324	B*D = Butt log * SED	-0.0429	0.0061	26.0	-7.04	< 0.0001
			$\hat{\sigma}^2_{tree} = 0.152$ ($p < 0.0001$), $\hat{\sigma}^2_{position} = 0.010$ ($p = 0.0307$), $\hat{\sigma}^2_{\varepsilon} = 0.200$					

$\hat{\beta}_j$ = the estimated regression coefficient for variable j, where $j = 0$ for the regression intercept and $j > 0$ for the independent variables in the equation.

t = the "Student's" t-statistic for testing whether $\beta_j = 0$ (may be approximate).

DBH = diameter at breast height.

SED = small-end diameter of the log.

R^2 = the statistical coefficient of determination (adjusted for the number of model parameters, based on either conditional or marginal residuals as determined on the original scale).

RMSE = the square root of the mean squared error (commonly known as "root mean squared error").

$\hat{\sigma}^2_i$ = the estimated variance of random-effect variable i; when $i = \varepsilon$, the variance estimate is for the error term or components of the error term.

B*D variable in table 16 all appear to have significantly influenced knot density in long logs. The negative sign on the B*D variable implies that butt logs tend to have lower knot densities than middle and upper logs; long logs with larger diameters and higher percentages of live knots tend to have higher knot densities.

Knot density in short logs—

As with tree stems and long logs, the results of regression analysis showed that the treatment variable was not significant. Live-knot fraction, elevation, and small-end diameter in combination with log position as defined by the B*D variable in table 16 were all found to be significant predictors of knot density in short logs—similar to the significant predictors in the long-log regression, and with identical signs on the coefficients in the two equations. However, because log diameter only appeared in the B*D term in this regression, its minus sign was an indicator of an inverse relationship between small-end log diameter in butt logs and knot density. Log diameter had no statistically significant effect on knot density in middle and upper short logs; thus the indirect treatment effect through the correlation between DBH and log small-end diameter likely influenced knot density only in butt logs. As with the regressions for tree stems and long logs, the fitted equation for short logs was highly significant overall but explained only a little more than a third of the variance in the knot-density data.

Effects of Treatment on Simulated Lumber Production

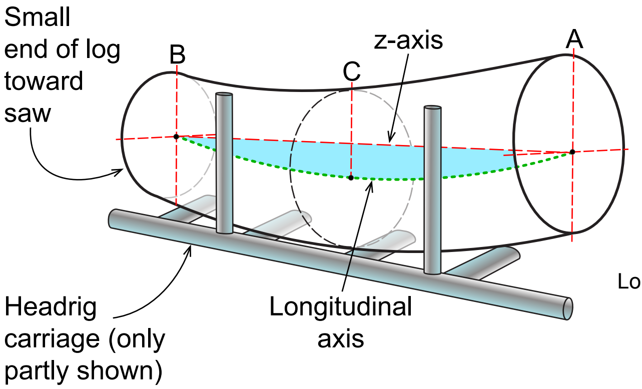
After many preliminary runs to evaluate and refine parameters, we made six final simulation runs using AUTOSAW, one run for each site and treatment combination (C2, C3, W2, W3, Y2, and Y3, where C is Cataract, W is Wildcat, and Y is Yachats; 2 corresponds to treatment T100 and 3 corresponds to treatment T60). Segregating the runs in this way was an arbitrary but convenient way to avoid exceeding the AUTOSAW limit of 99 short logs in a single simulation. Although the 88 Wildcat short logs could have been processed in a single run, the saw list for the other two sites was too large: 102 logs from Cataract and 134 logs from Yachats. We decided to handle all three sites the same way.

The instructions to the simulator (app. 3) were designed to simulate a sawmill producing mainly structural grade dimension lumber measuring 2 inches thick and 4 to 12 inches wide. Occasional 1-inch jacket boards were removed from the outside of the log as necessary to produce a properly sized rectangular cant for final sawing. Final piece sizes were produced by breakdown of the cant followed by edging.

Although detailed specifications for the AUTOSAW simulations are described in appendix 3, we provide a brief summary here. For logs that are not perfectly round (and few are), the initial presentation of the log to the saw has previously been shown to be an important consideration that can significantly influence lumber recovery (Todoroki et al. 2007). For this study it was not possible to determine how individual logs would be presented to the saw, because the logs were sold to several mills and our study did not include an in-mill recovery component. Therefore we arbitrarily assumed that the simulated sawmill would use a vertical bandsaw and that each log would be oriented with the small end toward the saw and with the y-axis of the log pointing vertically upward in the same configuration as when the log was originally measured. For logs with sweep, the orientation was with "horns up" (sometimes called sweep down), in which the longitudinal axis at the geometric center is located vertically below the z-axis as illustrated in figure 10; this orientation is often used to make the opening cut in Douglas-fir logs when the sawmill is not equipped for curve sawing (Monserud et al. 2004). We assumed that the sawmill would use half-taper sawing, a practice in which the cuts are aligned parallel to the center of the log. This is a commonly used method for sawing small Douglas-fir logs in local mills. Full-taper sawing, in which the cuts are aligned parallel to the edge of the log, is more commonly used when higher value logs are being cut. As previously mentioned, our goal was not to achieve the maximum possible rate of lumber recovery but rather to mimic the rate that would be considered typical of local sawmills.

Lumber Volume, Grade, and Value

Our analysis of products from simulated sawing was limited to lumber. Inevitably, some parts of each log are converted at the mill into sawdust or wood chips, either of which can be recovered and sold or used at the mill. In general, the value of these residual products is quite low, often depending on the local efficiencies



z-axis	A straight line connecting the geometric centers of the two ends of the log.
A and B	Reference points marking the two ends of the log.
C	The point on the log where the sweep offset from the z-axis to the longitudinal axis is largest.
Longitudinal axis	The geometric center of the log at each point along its length (curved unless the log is straight).

Figure 10—Horns-up orientation of a log with sweep, as it would be positioned on the headrig carriage for the opening cut; the opening cut is made on the far side of the log, beginning outside of point B and moving to a position outside of point A.

within a particular mill and whether it is part of an integrated processing facility. To the extent that an individual sawmill can use or sell the sawdust and wood chips it produces, our value estimates would need to be adjusted to reflect some of the additional value that would be captured.

The AUTOSAW runs produced one output file for each short log sawn. After running each simulation we compiled the results from all output files produced in that run into a single Microsoft Excel file using the software described in appendix 3. Table 17 shows part of a spreadsheet from one of the simulations, and table 18 summarizes the results from all six runs. The largest number of pieces produced was in 2×4 boards (41 percent of pieces and 19 percent of volume) but the largest volume produced (39 percent of the total for all simulations) was in 2×12 boards. Treatment T60 generally produced a slightly higher percentage of the wider pieces than treatment T100; 2×12 boards, for instance, accounted for 42 percent of the lumber volume sawn from treatment T60 logs compared to only 36 percent sawn from T100 logs. Because the emphasis was on dimension lumber, very few 1-inch pieces were produced and these were nearly all 1×4 and 1×6 boards. Only two 1×8 boards were sawn, both from a single log (C3-2041-2-1). The AUTOSAW output lists included no 1×10 or 1×12 boards.

From the simulations, 47 percent of the lumber volume came from the Yachats site (table 18). 41 percent of the sample trees were harvested from this site, which produced Forty-one percent of the short logs for simulated sawing. On average, these logs were somewhat larger in diameter than those from the other sites (table 8) and therefore produced more lumber per log.

Data in table 18 also show that 42 percent of the simulated lumber volume for all sites came from treatment T60 even though it was the source of only 36 percent of the sample trees (table 3) and 38 percent of the short logs (table 8). Logs from treatment T60 were generally larger in diameter than those from treatment T100 and therefore tended to produce more lumber per log.

Results are summarized from the sawing simulation for individual pieces of lumber (table 19), for lumber grouped by short logs (table 20), and for lumber grouped by sample trees (table 21). Data within each table are organized by site, treatment, and for all items (lumber, short logs, or trees) combined. Each table includes data on lumber production as measured in pieces, board-foot lumber volume, and estimated lumber value. The tables also present data in several grade groupings that are commonly used in the Douglas-fir sawmill industry. Although the highest dimension-lumber grade, select structural, is shown separately because of its importance as a general index of lumber quality, lumber assigned that grade is also included in the higher graded grouping (No. 2 and better), an aggregation of

Table 17—Part of the spreadsheet produced as an aggregation of data from AUTOSAW OUT files resulting from a single simulation run; although the summary is for all 93 short logs that were derived from sample trees in the light treatment (T100) of the Yachats site, the lower part of the spreadsheet shows individual pieces of lumber that were cut from only two of the logs (selected to illustrate the production of both 2-inch and 1-inch lumber)

AUTOSAW	Lumber summary by piece size		
Lumber production report	**Size**	**Pieces**	**Volume**
	Inches		*Board feet*
Lumber produced from:	2 × 4	330	2,560.00
Short logs from Yachats, Treatment T100	2 × 6	93	1,307.00
Number of logs sawn: 93	2 × 8	81	1,730.67
	2 × 10	56	1,603.33
	2 × 12	158	5,612.00
Volume percentage of lumber by thickness:	1 × 4	55	179.33
2-inch lumber: 97.8 percent	1 × 6	21	107.50
1-inch lumber: 2.2 percent	1 × 8	0	0
	1 × 10	0	0
	1 × 12	0	0
Totals		794	13,099.83

Log ID	Lumber piece ID[a]	Thick-ness	Width	Length	Autosaw grade	Volume	WWPA grade[b]
		- - *Inches* - -		*Feet*		*Board feet*	
Y2-1114-1-1	6a	2	4	7	O	4.67	No1 SLF
Y2-1114-1-1	7a	2	6	17	A	17.00	SelStr J&P
Y2-1114-1-1	7b	2	4	17	Q	11.33	No3 SLF
Y2-1114-1-1	8a	2	12	18	C	36.00	No2 J&P
Y2-1114-1-1	9a	2	12	18	D	36.00	No3 J&P
Y2-1114-1-1	10a	2	12	18	A	36.00	SelStr J&P
Y2-1114-1-1	11a	2	10	18	A	30.00	SelStr J&P
Y2-1114-1-1	12a	2	4	8	O	5.33	No1 SLF
Y2-1159-2-2	2a	1	6	10	4	5.00	Com4 COM
Y2-1159-2-2	4a	1	6	10	2	5.00	Com2 COM
Y2-1159-2-2	6a	2	4	7	Q	4.67	No3 SLF
Y2-1159-2-2	7a	2	8	18	D	24.00	No3 J&P
Y2-1159-2-2	8a	2	10	18	C	30.00	No2 J&P
Y2-1159-2-2	9a	2	10	18	E	30.00	Econ J&P
Y2-1159-2-2	10a	2	10	18	D	30.00	No3 J&P
Y2-1159-2-2	11a	2	4	16	O	10.67	No1 SLF
Y2-1159-2-2	11b	2	4	15	P	10.00	No2 SLF

[a] Piece identifiers are in two parts: a number signifying the order in which sawing cuts were made, followed by an alpha character indicating any piece that was subsequently split by the edger. Missing numbers indicate pieces that were discarded by the simulator.

[b] An initial designator indicating the grade (Select Structural, Number 1, Number 2, Number 3, Economy, Common 2, Common 4), and a second designator indicating the applicable grading rule (J&P = Joists & Planks, SLF = Structural Light Framing, COM = Common Boards). The selection of lumber shown here does not include all WWPA grades and rules for which AUTOSAW has been calibrated.

Table 18—Results from simulated sawing of logs from sample trees in Douglas-fir stands on the Oregon Coast Range 15 years after commercial thinning treatments—light thinning (T100) and moderate thinning (T60)

	Treatment T100				Treatment T60			
			Lumber produced				Lumber produced	
Study site	Short logs sawn	Lumber size	Number of pieces	Volume	Short logs sawn	Nominal lumber size	Number of pieces	Volume
		Inches		*Board feet*		*Inches*		*Board feet*
Cataract	66	2 × 4	180	1,354.67	36	2 × 4	86	610.67
		2 × 6	43	643		2 × 6	21	319
		2 × 8	52	1,137.33		2 × 8	38	820
		2 × 10	49	1,368.33		2 × 10	35	995
		2 × 12	51	1,804		2 × 12	63	2,212
		1 × 4	21	78.33		1 × 4	17	48
		1 × 6	4	24		1 × 6	8	43.50
		1 × 8	0	0		1 × 8	2	21.33
		All sizes	400	6,409.67		All sizes	270	5,069.50
Wildcat	43	2 × 4	122	882.67	45	2 × 4	150	1,112.67
		2 × 6	29	444		2 × 6	41	577
		2 × 8	31	678.67		2 × 8	25	520
		2 × 10	24	693.33		2 × 10	51	1,318.33
		2 × 12	30	1,060		2 × 12	66	2,312
		1 × 4	22	78.33		1 × 4	38	121.67
		1 × 6	2	7		1 × 6	9	36
		1 × 8	0	0		1 × 8	0	0
		All sizes	260	3,844		All sizes	380	5,997.67
Yachats	93	2 × 4	330	2,560	41	2 × 4	139	1,066
		2 × 6	93	1,307		2 × 6	35	483
		2 × 8	81	1,730.67		2 × 8	45	918.67
		2 × 10	56	1,603.33		2 × 10	29	768.33
		2 × 12	158	5,612		2 × 12	74	2,556
		1 × 4	55	179.33		1 × 4	17	53.67
		1 × 6	21	107.50		1 × 6	14	75
		1 × 8	0	0		1 × 8	0	0
		All sizes	794	13,099.83		All sizes	353	5,920.67
All sites	202	2 × 4	632	4,797.33	122	2 × 4	375	2,789.33
		2 × 6	165	2,394		2 × 6	97	1,379.
		2 × 8	164	3,546.67		2 × 8	108	2,258.67
		2 × 10	129	3,665		2 × 10	115	3,081.67
		2 × 12	239	8,476		2 × 12	203	7,080.
		1 × 4	98	336		1 × 4	72	223.33
		1 × 6	27	138.50		1 × 6	31	154.50
		1 × 8	0	0		1 × 8	2	21.33
		All sizes	1,454	23,353.50		All sizes	1,003	16,987.83

select structural, No. 1 (also called construction), and No. 2 (also called standard) dimension lumber. The lower graded grouping (No. 3 and economy) grouping consists of the No. 3 (also called utility) and the lowest quality dimension lumber (called economy grade). Together, the two groupings account for all of the grades for dimension lumber that were assigned by AUTOSAW in the simulations. For 1-inch jacket boards, we used the five WWPA (2005) common groupings normally reserved for pine, spruce, and cedar species. These five grades are grouped together because so few jacket boards were produced in the simulation. Prices used to determine the estimated lumber values are described below.

Lumber volume recovery—

AUTOSAW has previously been shown to provide reasonably close estimates of the volume of lumber from second-growth Douglas-fir logs. Barbour et al. (2003), for example, found that AUTOSAW simulations underestimated actual lumber production for a set of sample logs by only 10 to 15 percent, likely because the simulator avoids producing lumber with wane, which can reduce lumber grade. However, tolerance for wane can be adjusted on the simulator; and for this study we increased production by setting the maximum allowable wane to 0.4 inch (app. 3), twice the allowance used by Barbour et al. (2003). A 0.4-inch allowance for wane is not unusual in mills of the type that process Douglas-fir in the area, as verified by a database on second-growth Douglas-fir lumber recovery studies maintained by the wood-quality research team at the PNW Station. The study reported by Monserud et al. (2004) used an even larger maximum wane allowance, 0.47 inch.

Simulation results for individual pieces of lumber (table 19) are shown for all grades. Although the largest number of pieces was produced from logs extracted from the Yachats site, both the lumber volume per piece and value per piece were slightly higher for lumber produced from the Cataract site. The Yachats site had slightly larger logs on average than the other two sites (table 8), but it also had somewhat larger and more frequent knots (table 14). In addition, 27 percent of logs from the Yachats site had sweep compared to only 16 percent from the Cataract site and 19 percent from the Wildcat site. Sweep tends to reduce piece length and thus reduces both volume and value per piece of lumber recovered. The differences in volume and value per piece as shown in table 19, however, appear to be relatively minor within all of the aggregations. The simulated lumber production is summarized in number of pieces and in board-foot volume per log (table 20). For each level of aggregation, the table also shows the cubic recovery rate (cubic feet of lumber produced per cubic foot of log or tree, expressed as a percentage and calculated using rough-sawn lumber sizes rather than nominal sizes) and the lumber-overrun percentage. Lumber overrun is a common measure used in the sawmill industry,

Table 19—Quantity, volume, and value of lumber by piece produced from simulated sawing of short logs from sample trees in Douglas-fir stands on the Oregon Coast Range 15 years after commercial thinning treatments—light thinning (T100) and moderate thinning (T60)

	Dimension lumber				
Groupings	SelStr	No2&Btr	No3&Econ	1-inch	All grades
			Pieces of lumber sawn		
Cataract	234	476	142	52	670
Wildcat	187	424	145	71	640
Yachats	315	720	320	107	1,147
Treatment T100	423	949	380	125	1,454
Treatment T60	313	671	227	105	1,003
All lumber	736	1,620	607	230	2,457
			Lumber volume per piece (board feet)		
Cataract	19.65	18.22	18.24	4.14	17.13
Wildcat	18.18	17.47	15.12	3.42	15.38
Yachats	20.69	18.90	15.62	3.88	16.58
Treatment T100	18.61	17.65	16.12	3.80	16.06
Treatment T60	21.22	19.28	16.10	3.80	16.94
All lumber	19.72	18.33	16.11	3.80	16.42
			Lumber value (U.S. dollars per piece)		
Cataract	6.33	5.47	3.41	1.79	4.75
Wildcat	5.73	5.09	2.79	1.18	4.14
Yachats	6.61	5.51	2.84	1.38	4.38
Treatment T100	5.90	5.15	2.94	1.40	4.25
Treatment T60	6.84	5.73	3.00	1.42	4.66
All lumber	6.30	5.39	2.96	1.41	4.42

SelStr = Select Structural grade lumber.
No2&Btr = a composite category including select Structural, No. 1, and No. 2 grades.
No3&Econ = a composite category including No. 3 and economy grades.

calculated as board feet of lumber produced from a log or tree divided by the estimated board-foot volume of the log or tree. In this study, board-foot log volumes were estimated using Scribner scaling rules. Because Scribner tends to underestimate the volume of lumber that can be produced from second-growth logs, overrun is usually more than 100 percent. To avoid artifacts produced by scaling deductions, we used gross volumes in calculating both cubic recovery rate and overrun.

Each of the main groups in table 20 is subdivided into groups representing the position of the log within the standing tree (butt, middle, or upper). As one would expect, the number of pieces and the volume of lumber cut from the log is highest in butt logs and lowest in the upper logs. The average number of pieces sawn per log

Table 20—Average values (by log position) for selected attributes of lumber produced from simulated sawing of short logs from sample trees in Douglas-fir stands on the Oregon Coast Range 15 years after commercial thinning treatments—light thinning (T100) and moderate thinning (T60)

		Lumber pieces		Lumber volume (board feet)				Dimension lumber percentages by grade			Lumber value, in U.S. dollars per:			
Groupings	Log position	Dimension	1-inch	Dimension	1-inch	Cubic recovery	Overrun	SelStr	No2& Btr	No3& Econ	Log	MLT	MBF	CCF
						- - Percent - -								
Cataract	Butt	9.5	0.7	185.3	3.3	51.8	160	50.3	82.4	17.6	54.46	281	451	256
	Middle	6.8	0.4	135.8	2.2	49.0	169	32.9	71.2	28.8	37.78	268	453	231
	Upper	4.0	0.5	58.1	1.5	41.8	172	28.5	76.6	23.4	15.90	262	453	196
	All	6.1	0.5	110.4	2.1	46.3	168	34.3	75.8	24.2	31.18	268	453	220
Wildcat	Butt	10.5	0.7	198.1	2.8	50.9	163	45.9	88.8	11.2	56.80	279	450	248
	Middle	7.4	0.7	143.1	2.6	50.8	167	25.7	65.3	34.7	38.12	261	435	232
	Upper	4.0	0.9	44.6	2.9	39.2	189	18.9	71.6	28.4	12.24	252	480	178
	All	6.5	0.8	109.1	2.8	45.4	176	26.9	73.3	26.7	30.09	260	459	210
Yachats	Butt	12.3	0.7	240.0	3.1	53.3	159	56.7	84.6	15.4	69.78	286	455	266
	Middle	9.2	0.8	176.4	3.6	51.9	166	25.0	68.0	32.0	45.68	254	422	230
	Upper	4.7	0.9	65.7	2.7	42.2	197	16.3	65.8	34.2	17.06	246	485	187
	All	7.8	0.8	138.8	3.1	47.8	179	27.4	70.3	29.7	37.51	257	457	217
Treatment T100	Butt	10.2	0.7	192.7	2.8	51.4	164	47.1	82.1	17.9	55.05	277	451	249
	Middle	7.7	0.6	145.5	2.3	50.2	167	26.7	68.5	31.5	38.21	258	431	227
	Upper	4.1	0.6	53.2	2.1	41.2	186	20.4	67.5	32.5	13.80	249	464	184
	All	6.6	0.6	113.3	2.3	46.4	175	28.1	70.9	29.1	30.59	258	450	212
Treatment T60	Butt	12.2	0.8	244.0	3.5	53.6	155	59.7	90.4	9.6	72.52	292	454	273
	Middle	8.2	0.8	169.4	3.8	51.4	167	29.5	68.2	31.8	45.96	265	442	237
	Upper	4.7	0.9	64.6	2.8	41.4	188	21.5	76.1	23.9	17.93	259	490	192
	All	7.4	0.9	136.0	3.3	47.2	174	31.8	76.2	23.8	38.32	268	467	223
All short logs	Butt	10.9	0.7	211.3	3.1	52.2	161	51.6	85.1	14.9	61.40	282	452	258
	Middle	7.9	0.7	154.6	2.9	50.7	167	27.8	68.4	31.6	41.17	260	435	231
	Upper	4.3	0.8	57.5	2.4	41.3	187	20.8	70.8	29.2	15.36	253	474	187
	All	6.9	0.7	121.8	2.7	46.7	175	29.4	72.9	27.1	33.50	261	456	216

SelStr = Select Structural lumber grade.
No2&Btr = a composite category including select Structural, No. 1, and No. 2 grades.
No3&Econ = a composite category including No. 3 and economy grades.
MLT = thousand board-feet lumber tally.
MBF = thousand board feet of gross log volume, Scribner scale.
CCF = hundred cubic feet of gross log volume.

was smallest for Cataract and largest for Yachats. It was larger in logs from treatment T60. Similarly, lumber volume produced per log was highest overall at Yachats, with especially large margins for butt and middle logs. Cubic recovery rates for Yachats were also higher than those for the other sites. Despite its relatively high recovery rates from butt and middle logs, the Wildcat site had the lowest lumber volume per log, primarily because of higher taper and shorter lengths. Lumber volume recovered per log was higher in logs from treatment T60 than in those from

Table 21—Average values of selected attributes of lumber produced from the simulated sawing of sample trees in Douglas-fir stands on the Oregon Coast Range 15 years after commercial thinning treatments—light thinning (T100) and moderate thinning (T60)

	Lumber pieces		Lumber volume (board feet)				Dimension lumber percentages by grade			Lumber value, in U.S. dollars per:			
Groupings	Dimension	1-inch	Dimension	1-inch	Cubic recovery	Overrun	SelStr	No2& Btr	No3& Econ	Tree	MLT	MBF	CCF
					- - - *Percent* - - -								
Cataract	30.9	2.6	563.2	10.8	48.3	164	36.1	74.5	25.5	159.04	269	442	229
Wildcat	29.9	3.7	505.2	12.8	48.3	167	31.3	73.6	26.4	139.37	262	436	223
Yachats	38.5	4.0	689.1	15.4	50.0	169	34.2	72.3	27.7	186.14	263	443	231
Treatment T100	31.6	3.0	544.7	11.3	48.3	168	31.6	71.2	28.8	147.14	260	436	221
Treatment T60	37.4	4.4	691.2	16.6	50.3	165	38.1	77.2	22.8	194.79	273	449	240
All sample trees	33.7	3.5	598.0	13.2	49.0	167	33.9	73.4	26.6	164.47	265	441	228

SelStr = Select Structural lumber grade.
No2&Btr = a composite category including select Structural, No. 1, and No. 2 grades.
No3&Econ = a composite category including No. 3 and economy grades.
MLT = thousand board-feet lumber tally.
MBF = thousand board feet of gross log volume, Scribner scale.
CCF = hundred cubic feet of gross log volume.

treatment T100, and higher in logs from trees grown on north-facing slopes than in those from trees grown on south-facing slopes.

Results for pieces sawn and volume produced per tree (table 21) generally follow the same patterns as exhibited for logs. These values are highest for Yachats and lowest for Wildcat and higher for trees from treatment T60 than for those from treatment T100. Cubic recovery rates and overrun follow similar trends but differences within and among the groups were relatively small.

Lumber grade recovery—

In second-growth Douglas-fir, decay is uncommon and lumber grades are primarily influenced by surface defects such as knots, the presence of juvenile wood (not considered in this study because of AUTOSAW limitations), and sawing imperfections such as wane (WWPA 2005). AUTOSAW estimates lumber grade using WWPA (2005) rules on knot size and distribution, assuming that surface knots originate in the pith at the center of the log and grow to the surface in the shape of a cone with its vertex located at the pith and its base at the surface of the log. Although AUTOSAW accounts for differences between live and dead knots by modeling the live portion of the embedded branch as a cone and the dead portion as a cylinder (Todoroki 1997), we could not determine what percentage of an embedded branch remained alive without cutting into the log or using expensive procedures such as tomography (Taylor et al. 1984). Thus we opted to follow the assumption common in studies of simulated Douglas-fir sawing (Todoroki et al. 2005) that 80 percent of the length of all such branches was alive—the live portion extending 80 percent of the distance to the surface with the remaining 20 percent manifesting as dead knots in lumber produced from the outer part of the log.

Although knots are usually the most important determinant of lumber grade in second-growth Douglas-fir, wane is also an important consideration. AUTOSAW estimates wane from recorded diameters at profile points located along the length of the log and uses the estimation to adjust lumber grade, discard pieces with excessive wane, trim them to shorter lengths, or edge them to narrower widths.

Like many sawing simulators, AUTOSAW tends to overestimate grade recovery (table 19) partly because it cannot account for imperfections beyond knots, wane, sweep, and crook. It also cannot account for fully embedded branches that are hidden beneath the surface of the log—branches (most often occurring in butt logs) that were pruned or died early in the life of the tree and were later grown over and no longer evident on the surface. Although we removed bark from the logs where it appeared that a surface knot might be present, the thick bark typical of Douglas-fir can easily hide knots and it is unlikely that we found all of them. Although the “All grades” column of table 19 shows few major differences within the various aggregations of lumber volume per piece as discussed in the previous section, the differences are somewhat larger within individual grade groupings. As an example, for all grades combined the mean volume per piece (table 19) was somewhat larger for Cataract than for the other two sites; but within both the select-structural and No. 2 and better groupings, volume per piece was highest on the Yachats site where the logs were generally somewhat larger. But the volume per piece graded as No. 3 and economy was substantially larger for Cataract than for the other two sites. Also, the larger logs from treatment T60 yielded larger average lumber volumes per piece in the select-structural and the No. 2 and better groupings than logs from T100, whereas the average volumes per piece were nearly the same in other grades for the two treatments.

Figure 11 summarizes dimension-lumber grade recovery from short logs according to the location of the log in the tree and the site or the thinning treatment. The percentage of select-structural lumber was generally lower in logs originating from higher in the tree. Butt logs from Wildcat produced less select-structural lumber and more No. 2 lumber than butt logs from the other two sites; however, they also produced less of the two lowest grades. Upper logs from Yachats produced the most lumber in the two lowest grades, the consequence of very large knots in some of the upper logs from that site. Logs from treatment T60 generally produced somewhat more select-structural lumber than those from treatment T100, and also produced less lumber in the lowest grade grouping. Although knots on the logs from treatment T60 were generally larger than those from treatment T100, any negative effect of the larger knots apparently was mitigated by the fact that logs from treatment T60 also tended to have larger diameters and thus produced somewhat wider pieces of lumber.

Tables 20 and 21 show the percentages of total dimension-lumber volume that was produced in the three grade groupings. The percentage of No. 2 and better lumber plus the percentage of No. 3 and economy add to 100; the select-structural grade is a subset of the No. 2 and better grouping, but it also serves as an additional measure of wood quality. This grade always constitutes more than half of the No. 2 and better grouping in butt logs (table 20), always less than half in middle logs; and typically less than a third in upper logs. The percentage of lumber graded as No. 3 and economy was about the same for middle logs and upper logs at Cataract and Wildcat but it was largest for upper logs at Yachats. The percentages of lumber in the select-structural and the No. 2 and better groupings were substantially higher for treatment T60 than for treatment T100.

For trees as a whole (table 21), select-structural lumber constituted somewhat less than half of the No. 2 and grouping in all categories with only minor differences occurring among the three sites. However, the difference in grade recovery between the two treatments was more marked, with trees from treatment T60 yielding a larger percentage of lumber in the select-structural and No. 2 and better groupings as compared to the No. 3 and economy grouping.

Lumber value recovery—

The price of a piece of lumber depends on dimensions and grade, meaning that the volume of lumber recovered by grade at each price level determines the value of the logs and trees from which the lumber was processed. Such information is of considerable interest both to landowners who sell trees and to loggers who buy trees and sell logs. Because lumber prices tend to move rapidly as economic conditions change, the set of prices used for any analysis only represents a snapshot of the lumber market at a particular moment in time. For the 2008-to-2009 thinning operations in this study, lumber prices had dropped significantly compared with much of the preceding decade. For this study, we chose prices reported by sawmills in 2010, when the lumber market had recovered to a more normal level. The price series were taken from Random Lengths (2011) and WWPA (2011) and represented average prices by lumber grade. We assumed that the lumber would be kiln-dried and surfaced before being sold.

Estimated lumber value per piece is shown by grade grouping in table 19. Variations within a single grade, among sites or other major groups, result from the fact that the same grades may be assigned to pieces of different widths and lengths

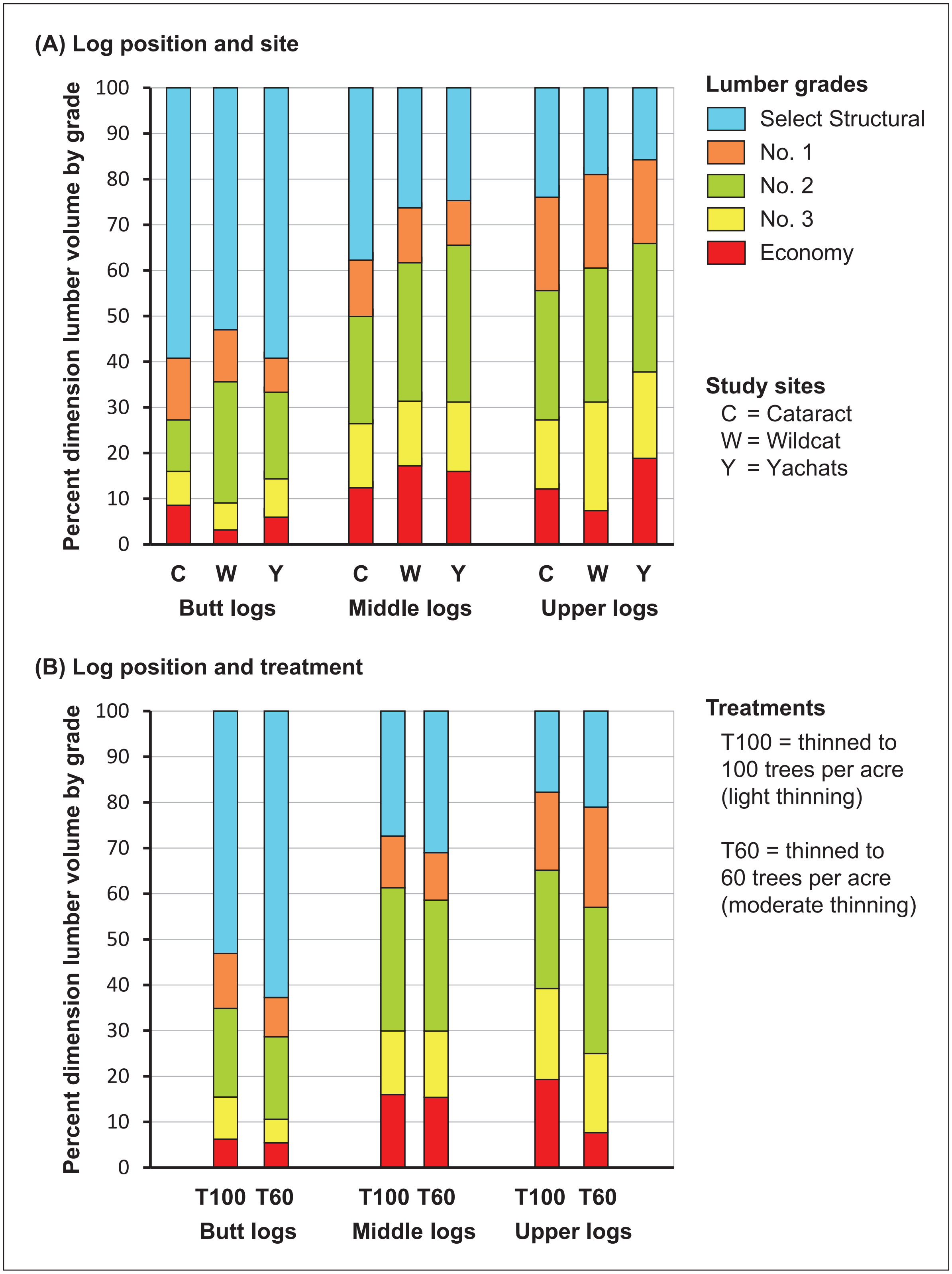


Figure 11—Recovery of dimension lumber by grade as influenced by log position within sample trees harvested on Douglas-fir stands in the Oregon Coast Range 15 years after habitat-improvement thinning treatments, displayed for (A) the three study sites and (B) the two thinning treatments.

(and thus different volumes per piece). As an example, the average value of select-structural lumber from the Wildcat site was $5.73 per piece compared to $6.61 for the same grade of lumber from Yachats. The reason for this 15-percent difference is that a higher percentage of select-structural lumber from the Yachats sites was in the wider—and higher priced—sizes. Nearly 51 percent of the dimension lumber graded as select structural from Yachats was in 2×12 pieces compared to only 38 percent from Wildcat. Although value per piece is also affected by piece length, the average lengths of select-structural 2×12 lumber from the two sites differed by only 0.08 foot.

As with volume per piece (table 19), lumber value per piece was higher for lumber from treatment T60 than from treatment T100, a difference that is especially noticeable for lumber in the select-structural and the No. 2 and better grades.

Lumber values are shown in dollars per short log (table 20) or per tree (table 21) plus three additional measures commonly used in forestry: $/MLT (dollars per thousand board feet of lumber tally), $/MBF (dollars per thousand board feet of gross Scribner log or tree volume), and $/CCF (dollars per hundred cubic feet of gross log or tree volume). These measures were all generally highest for butt logs and lowest for upper logs. Lumber value per log (table 20) and per tree (table 21) were highest for the Yachats site and lowest for Wildcat, but the value in dollars per thousand board feet of lumber tally was highest for Cataract. All measures of lumber value were higher for treatment T60 than for treatment T100, with some of the differences substantial. The value of lumber recovered per log (table 20), for example, was more than 30 percent higher for butt logs from treatment T60 than for butt logs from treatment T100, and the value of lumber recovered per tree (table 21) was 32 percent higher for treatment T60 than treatment T100.

Statistical Analysis of Lumber Recovery

This section presents the results of statistical analyses on lumber recovery by volume, grade, and value for trees and for short logs. We did not include long logs because they are not processed directly into lumber. Trees are included because they are sold by landowners and their value depends on the products that can be recovered from them.

The regression model to which the data were fit in the analysis of lumber recovery from tree stems and short logs was:

$$E(Y)=\beta_0+\beta_1D+\beta_2L+\beta_3LF+\beta_4K+\beta_5KD+\beta_6S+\beta_7T+\beta_8B+\beta_9U+\beta_{10}(D*B)+\beta_{11}(D*U) \qquad (2)$$

where:

Y = the response variable, a relevant measure of lumber volume, grade, or value recovered from trees or from short logs,

βj = parameters estimated via linear regression, j = 0 through 11,
D = an appropriate function of diameter, in inches (DBH for tree stems, small-end diameter for short logs),
L = an appropriate function of the length of the merchandized portion of the tree stem or length of the log, in feet,
LF = live-knot fraction (live knots in the tree stem or short log divided by the total surface knots recorded in each merchandized tree stem or short log),
K = knot density, measured in knots per foot of merchandized tree stem or short log,
KD = average knot diameter, in inches, per tree or per log,
S = the maximum sweep offset recorded for a log, in inches (used for short-log analyses only),
T = a dummy variable for treatment (T = 0 for trees from treatment T100 and T = 1 for trees from treatment T60),
B = for logs only, a dummy variable for log position (B = 1 for butt logs, B = 0 otherwise),
U = for logs only, a dummy variable for log position (U = 1 for upper logs, U = 0 otherwise),
$D*B$ = for logs only, the log diameter or its transformation (D) multiplied by the dummy variable for butt logs (B),
$D*U$ = for logs only, log diameter or its transformation (D) multiplied by the dummy variable for upper logs (U).

For the short-log analyses, equation (2) included a measure of log sweep (variable S) but did not include crook. This is because only six of the 324 short logs exhibited crook (table 11), a sample that we considered too small for a satisfactory statistical analysis. In contrast, 76 short logs (nearly one out of four) had measurable sweep.

Simultaneously with the regression analysis we also evaluated potential random effects for site and for site by treatment. For short logs, nonconstant variance related to log position was also tested and included in the model where appropriate.

Lumber volume recovery regression analysis—
The regression model described in equation (2) was used to fit data for volume recovery from trees and short logs in accordance with the following specifications:

- The response variable was defined as the natural logarithm of the volume of green lumber, in cubic feet, produced per tree stem or per short log.
- The function of diameter used as an independent variable was defined as the natural logarithm of DBH for tree stems and of small-end diameter for short logs, both in inches.

- The function of length used as an independent variable was defined as the natural logarithm of merchandized stem length for tree stems and of log length, both in feet.

We used these transformations primarily because of nonlinearities observed when the data were plotted; however, we also considered effects on the statistical residuals.

Table 22 summarizes results from the regression analyses. For tree stems, none of the random effects were statistically significant. Volume recovery per tree was strongly related to DBH, tree elevation, and the length of the merchandized stem. The estimated parameters for DBH and stem length were both positive numbers, indicating that as DBH and stem length increased, the volume of lumber recovered from the tree also tended to increase. Because of the logarithmic transformations, the effects of these two variables on expected volume recovery were nonlinear. DBH had a strong effect on expected volume recovery and this effect increased nonlinearly as the diameter increased (fig. 12). Because DBH was significantly affected by treatment (table 1), we concluded that treatment had an indirect effect on volume recovery. Figure 12 also shows the effect of stem length on volume recovery. The regression relationship described both treatment groups without a treatment parameter; however, a statistical contrast evaluating the difference in the values predicted from this regression at each level of treatment DBH, given the assumption of common elevations and tree lengths, indicates significant differences in those predicted values on the logarithmic scale (p-value for difference < 0.0001).

For short logs (table 22), site by treatment was significant as a random effect; nonconstant variance resulting from the position of the log within the tree was also significant and was thus included in the model. In the fixed-effects analysis, the volume of lumber produced per log was strongly related to small-end diameter, the live-knot fraction, and log length. The effect of small-end diameter was further increased in upper logs through the D*U interaction variable from equation (2). As shown in figure 13, the influence of small-end log diameter on lumber volume recovered from short logs was similar to the influence of DBH on lumber volume recovered from trees (fig. 12). The regression parameter for the D*U interaction variable was a positive number; however, upper logs would routinely be expected to produce somewhat less lumber volume at any small-end diameter because they are generally shorter than logs from the butt or middle positions in the tree. For this reason, the graph in figure 13 reflects a different average log length for upper logs than for butt and middle logs.

Table 22—Results of regression analyses for the natural logarithm ($\log_e$) of green lumber volume in cubic feet produced from sample trees in Douglas-fir stands on the Oregon Coast Range 15 years after commercial thinning treatments; variables whose parameters were not significantly different from zero at α = 0.05 have been excluded and overall fit values were calculated on the original scale (cubic feet)

	Overall fit		Parameter estimates for individual variables					
Level of analysis	Statistic	Value	Regression variable	$\hat{\beta}_j$	Standard error	Degrees of freedom	t	p value
Tree stems	Adjusted R^2-*conditional*	0.937	Intercept	-5.7511	0.4333	62	-13.27	< 0.0001
	Adjusted R^2-*marginal*	0.937	D = $\log_e$ of DBH (inches)	2.3544	0.0779	62	30.23	< 0.0001
	RMSE-*marginal*	4.6672	E = Elevation (feet)	-0.0003	0.0001	62	-3.32	0.0015
	Observations	66	L = $\log_e$ of Merchandized stem length (feet)	0.6179	0.1127	62	5.48	< 0.0001
			$\hat{\sigma}^2_{\varepsilon} = 0.0169$					
Short logs	Adjusted R^2-*conditional*	0.987	Intercept	-6.9904	0.1860	305.2	-37.59	< 0.0001
	Adjusted R^2-*marginal*	0.987	D = $\log_e$ of SED (inches)	2.2110	0.0289	248.5	101.15	< 0.0001
	RMSE-*marginal*	0.6238	LF = Live-knot fraction	0.1115	0.0292	226.3	3.82	0.0002
	Observations	324	L = $\log_e$ of Length (feet)	1.2182	0.0659	312.8	18.48	< 0.0001
			U*D = Upper log* [$\log_e$ of SED (inches)]	0.0268	0.0113	258.7	2.37	0.0183
			$\hat{\sigma}^2_{site,treatment} = 0.0005$ ($p = 0.0018$),					
			$\hat{\sigma}^2_{\varepsilon,butt}, \hat{\sigma}^2_{\varepsilon,middle}, \hat{\sigma}^2_{\varepsilon,upper} = (0.0058, 0.0053, 0.0365)$ ($p < 0.0001$)					

$\hat{\beta}_j$ = the estimated regression coefficient for variable j, where $j = 0$ for the regression intercept and $j > 0$ for the independent variables in the equation.
t = the "Student's" t-statistic for testing whether $\beta_j = 0$ (may be approximate).
DBH = diameter at breast height.
SED = small-end diameter of the log.
R^2 = the statistical coefficient of determination (adjusted for the number of model parameters, based on either conditional or marginal residuals as determined on the original scale).
RMSE = the square root of the mean squared error (commonly known as "root mean squared error").
$\hat{\sigma}^2_i$ = the estimated variance of random-effect variable i; when $i = \varepsilon$, the variance estimate is for the error term or components of the error term.

Lumber grade recovery regression analysis—

The regression model of equation (2) was used to fit data to regression equations for grade recovery from trees (table 23) and short logs (table 24) in accordance with the following specifications:

- The analysis was limited to dimension lumber because the 1-inch lumber from the sawing simulations represented only a small percentage of the total lumber produced.
- The response variable was defined as the percentage of total dimension lumber produced within each of the three grade groupings.

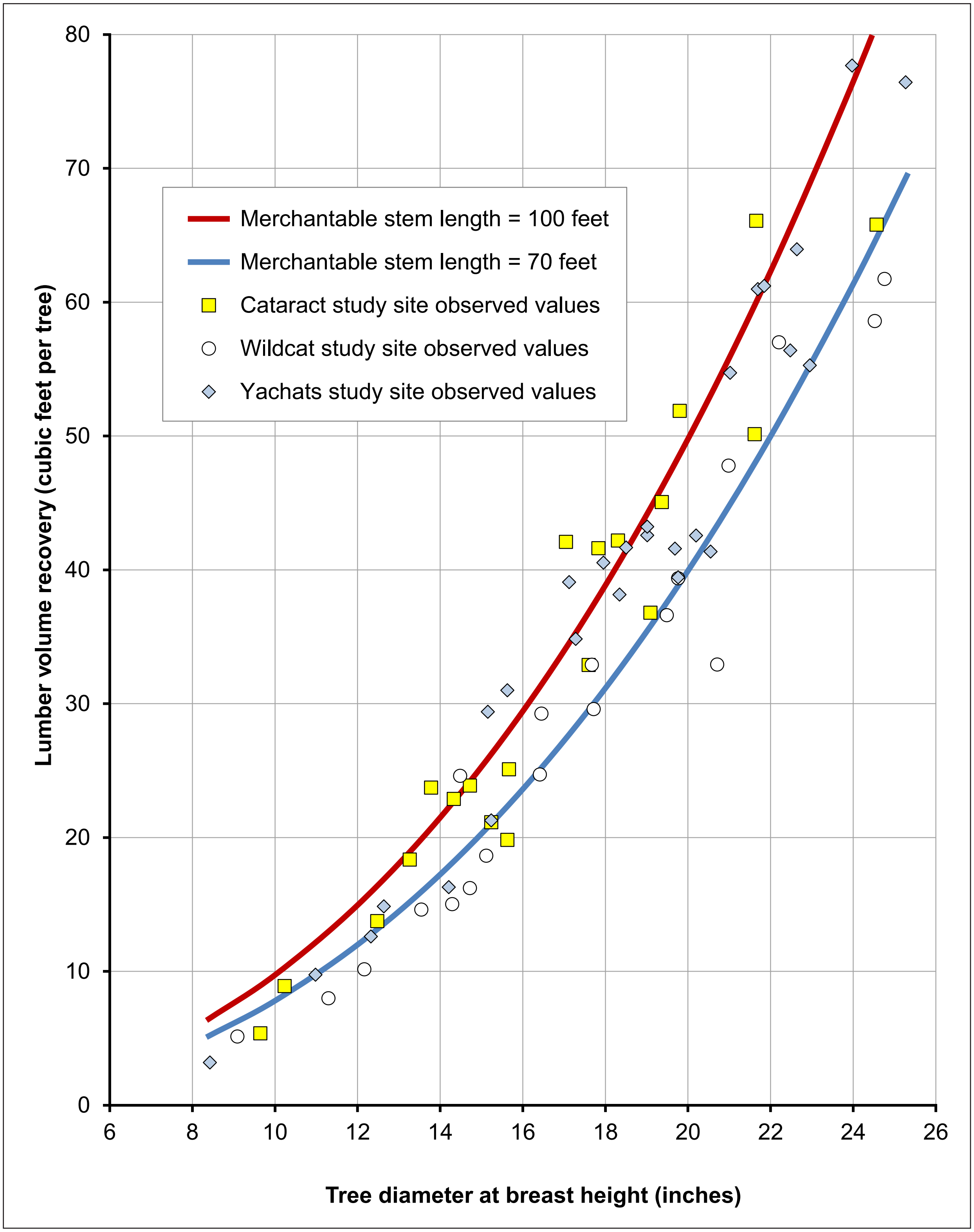


Figure 12—Lumber recovery as influenced by diameter at breast height for sample trees harvested on Douglas-fir stands in the Oregon Coast Range 15 years after habitat-improvement thinning treatments; for the two regression lines, merchandized stem length was set at approximately one standard deviation above and below the overall average value of 85.8 feet to illustrate the effect of merchandized stem length on volume recovery.

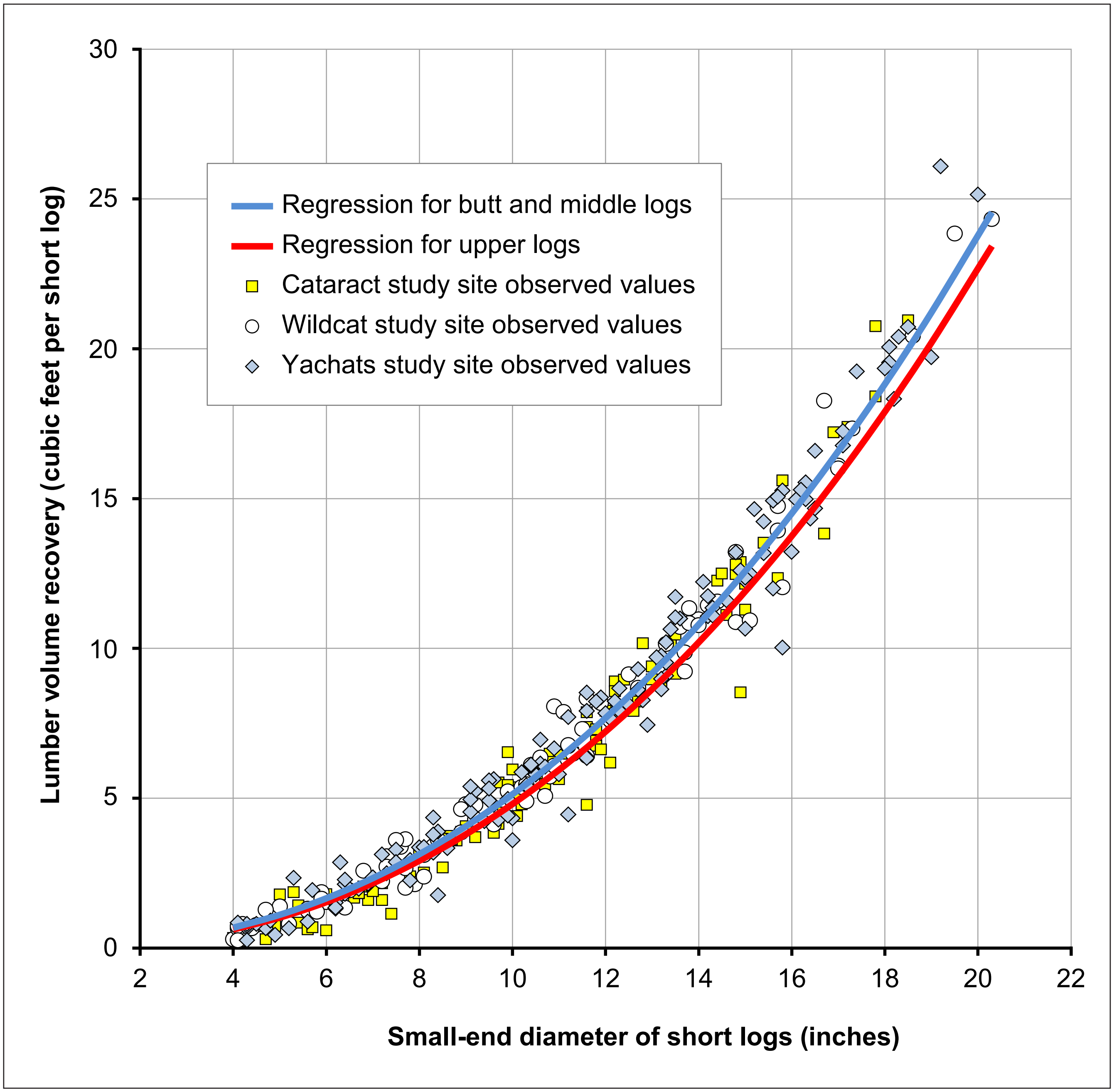


Figure 13—Lumber recovery as influenced by small-end diameter and log position within the tree for short logs that were cut from sample trees harvested on Douglas-fir stands in the Oregon Coast Range 15 years after habitat-improvement thinning treatments; for the two regression lines, log lengths were set at average values—one for butt and middle logs combined and the other for upper logs.

- When used as an independent variable, diameter was defined as the inverse of DBH for tree stems and the inverse of small-end diameter for short logs, both in inches.
- The function of length used as an independent variable was the merchandized stem length for tree stems and log length for short logs, both in feet.

Select-structural lumber was fit separately from other grades because of its importance as a general quality indicator; however, it is also included along with No. 1 and No. 2 lumber in the No. 2 and better grouping. To avoid double counting, we opted to calculate recovery rates of lower graded lumber as complements to the relevant No. 2 and better grade regression equations using regression analysis. No significant random effects were found for either the tree or short-log analysis. To better show the relationships between the complementary lumber-grade groupings, we somewhat altered the presentation in tables 23 and 24 from what was used for other regression analyses in this report.

For lumber produced per tree (table 23), statistically significant variables always included inverse DBH, live-knot fraction, and mean knot diameter. The separate equation for select-structural lumber also included knot density as measured by knots per foot of merchandized stem length. For both select-structural lumber and the No. 2 and better grade groupings, the percentage of dimension lumber increased with DBH but at a decreasing rate; increased as the live-knot fraction increased; and decreased as mean knot diameter increased. The percentage of select-structural lumber also decreased as knot density increased. Both regression equations were strongly significant but they explained less than a third of total variance in the data (No. 2 and better grouping) or slightly more than half of the variance (select structural). An analysis of data by log position for lumber produced per short log (table 24) showed that the diameter variable was invariably the inverse of small-end log diameter. Results were statistically significant in all regression equations, with the negative sign indicating that the percentage of lumber produced in the select-structural or No. 2 and better grades increased with small-end diameter but at a decreasing rate. This is evident in figure 14, as is the complementary relationship between the No. 2 and better and the No. 3 and economy grade groupings for each log position.

Knot density was statistically significant for all regressions except select-structural lumber from upper logs; however, higher knot density alone would be expected to reduce the percentage of dimension lumber in the higher grades. Live-knot fraction and average knot diameter were significant in all regressions for

Table 23—Results of regression analyses on dimension-lumber volume recovery by grade from sample trees in Douglas-fir stands on the Oregon Coast Range 15 years after commercial thinning treatments; volumes for each grade group are expressed as a fraction of the total dimension lumber recovered from the tree and variables whose parameters were not significantly different from zero at α = 0.05 have been excluded

Group	Lumber grade group[a]	Regression variable[b]	$\hat{\beta}_j$	Standard error	t	p value	Number of observations	Adjusted R^2	Wald statistic	p value
Trees	Select Structural	Intercept	1.1129	0.14253	7.81	< 0.0001	66	0.53	83.56	< 0.0001
		D = 1/DBH (inches)	-6.629	1.0651	-6.22	< 0.0001				
		LF = Live-knot fraction	0.51922	0.096146	5.4	< 0.0001				
		K = Knots per foot	-0.14474	0.028067	-5.16	< 0.0001				
		KD = Mean knot diameter (inches)	-0.278	0.077223	-3.6	0.0003				
	No. 2 & Better	Intercept	1.099	0.14643	7.51	< 0.0001	66	0.3	30.71	< 0.0001
		D = 1/DBH (inches)	-4.1813	1.1812	-3.54	0.0004				
		LF = Live-knot fraction	0.47978	0.11443	4.19	< 0.0001				
		KD = Mean knot diameter (inches)	-0.28679	0.091692	-3.13	0.0018				
	No. 3 & Economy	Intercept	-0.099							
		D = 1/DBH (inches)	4.1813							
		LF = Live-knot fraction	-0.47978							
		KD = Mean knot diameter (inches)	0.28679							

$\hat{\beta}_j$ = the estimated regression coefficient for variable j, where j = 0 for the regression intercept and j > 0 for the independent variables in the equation.

t = the "Student's" t-statistic for testing whether β_j = 0 (may be approximate).

R^2 = the statistical coefficient of determination (adjusted for the number of model parameters, based on either conditional or marginal residuals as determined on the original scale).

No. 2 & Better = a composite grade group including select Structural, No. 1, and No. 2 lumber grades.

No. 3 & Economy = a composite grade group including No. 3 and Economy lumber grades.

DBH = diameter at breast height.

The horizontal dashed line separates two lumber groups for which only a single regression equation was calculated (for No. 2 & Better), with parameters for No. 3 & Economy determined by complementarity since the percentage of volume recovered in the two groups must add to 100 percent.

[a] The No. 2 & Better grade group and the No. 3 & Economy grade group are complements whose recovery fractions (the dependent variable) must add to 1. Therefore lumber recovery for the No. 2 & Better group was fit to the regression parameters and then the values of the parameters for the No. 3 & Economy grade group were calculated as complements by construction. Fit statistics for the two groups were computed only for the No. 2 & Better grade group.

[b] Dependent variables were constrained to be between 0 and 1; Tobit regressions were fit with these restrictions (SAS 9.2 PROC QLIM with lower and upper bound specifications). A joint Wald test for nonzero coefficients was computed for each regression.

Table 24—Results of regression analyses on lumber-grade recovery by volume from short logs (by log position) from sample trees in Douglas-fir stands on the Oregon Coast Range 15 years after commercial thinning treatments; volumes for each grade are expressed as a fraction of the total dimension lumber recovered from the log and variables whose parameters were not significantly different from zero at α = 0.05 have been excluded

Group	Lumber grade group[a]	Regression variable[b]	$\hat{\beta}_j$	Standard error	*t*	p value	Number of observations	Adjusted R^2	Wald statistic	p value
Butt short logs	Select Structural	Intercept	1.36434	0.094559	14.43	< 0.0001	66	0.60	97.76	< 0.0001
		D = 1/SED (inches)	-6.78243	1.071274	-6.33	< 0.0001				
		K = Knots per foot	-0.26503	0.033503	-7.91	< 0.0001				
	No. 2 & Better	Intercept	1.58107	0.21012	7.52	< 0.0001	66	0.22	24.85	< 0.0001
		T = Treatment	0.09163	0.04516	2.03	0.0424				
		D = 1/SED (inches)	-2.60379	1.07145	-2.43	0.0151				
		K = Knots per foot	-0.08375	0.03286	-2.55	0.0108				
		KD = Mean knot diameter (inches)	-0.54914	0.21253	-2.58	0.0098				
	No. 3 & Economy	Intercept	-0.58107							
		T = Treatment	-0.09163							
		D = 1/SED (inches)	2.60379							
		K = Knots per foot	0.08375							
		KD = Mean knot diameter (inches)	0.54914							
Middle short logs	Select Structural	Intercept	1.3438	0.18543	7.25	< 0.0001	110	0.28	44.20	< 0.0001
		D = 1/SED (inches)	-4.4840	1.1071	-4.05	< 0.0001				
		K = Knots per foot	-0.16054	0.032495	-4.94	< 0.0001				
		LF = Live-knot fraction	0.62045	0.12772	4.86	< 0.0001				
		KD = Mean knot diameter (inches)	-0.49489	0.11658	-4.25	< 0.0001				
	No. 2 & Better	Intercept	2.0129	0.20900	9.63	< 0.0001	110	0.31	57.80	< 0.0001
		D = 1/SED (inches)	-5.8342	1.2195	-4.78	< 0.0001				
		K = Knots per foot	-0.16404	0.037059	-4.43	< 0.0001				
		LF = Live-knot fraction	0.99746	0.15217	6.55	< 0.0001				
		KD = Mean knot diameter (inches)	-0.65616	0.13305	-4.93	< 0.0001				
	No. 3 & Economy	Intercept	-1.0129							
		D = 1/SED (inches)	5.8342							
		K = Knots per foot	0.16404							
		LF = Live-knot fraction	-0.99746							
		KD = Mean knot diameter (inches)	0.65616							

Table 24—Results of regression analyses on lumber-grade recovery by volume from short logs (by log position) from sample trees in Douglas-fir stands on the Oregon Coast Range 15 years after commercial thinning treatments; volumes for each grade are expressed as a fraction of the total dimension lumber recovered from the log and variables whose parameters were not significantly different from zero at α = 0.05 have been excluded (continued)

Group	Lumber grade group[a]	Regression variable[b]	$\hat{\beta}_j$	Standard error	*t*	p value	Number of obser-vations	Adjusted R^2	Wald statistic	p value
Upper short logs	Select Structural	Intercept	1.5877	0.32891	4.83	< 0.0001	148	0.19	46.69	< 0.0001
		D = 1/SED (inches)	-4.8108	0.89432	-5.38	< 0.0001				
		L = Log length (feet)	-0.030569	0.013510	-2.26	0.0237				
		LF = Live-knot fraction	0.66564	0.14361	4.64	< 0.0001				
		KD = Mean knot diameter (inches)	-0.67599	0.11512	-5.87	< 0.0001				
	No. 2 & Better	Intercept	2.2004	0.39077	5.63	< 0.0001	148	0.32	83.14	< 0.0001
		D = 1/SED (inches)	-3.6982	0.98117	-3.77	0.0002				
		L = Log length (feet)	-0.035119	0.015515	-2.26	0.0236				
		K = Knots per foot	-0.15048	0.059039	-2.55	0.0108				
		LF = Live-knot fraction	1.4483	0.17893	8.09	< 0.0001				
		KD = Mean knot diameter (inches)	-0.78932	0.13201	-5.98	< 0.0001				
	No. 3 & Economy	Intercept	-1.2004							
		D = 1/SED (inches)	3.6982							
		L = Log length (feet)	0.035119							
		K = Knots per foot	0.15048							
		LF = Live-knot fraction	-1.4483							
		KD = Mean knot diameter (inches)	0.78932							

$\hat{\beta}_j$ = the estimated regression coefficient for variable j, where j = 0 for the regression intercept and j > 0 for the independent variables in the equation.

t = the "Student's" t-statistic for testing whether β_j = 0 (may be approximate).

R^2 = the statistical coefficient of determination (adjusted for the number of model parameters, based on either conditional or marginal residuals as determined on the original scale).

No. 2 & Better = a composite grade group including select Structural, No. 1, and No. 2 lumber grades.

No. 3 & Economy = a composite grade group including No. 3 and economy lumber grades.

SED = small-end diameter of the log.

The horizontal dashed line separates two lumber groups for which only a single regression equation was calculated (for No. 2 & Better), with parameters for No. 3 & Economy determined by complementarity since the percentage of volume recovered in the two groups must add to 100 percent.

[a] The No. 2 & Better grade group and the No. 3 & Economy grade group are complements whose recovery fractions (the dependent variable) must add to 1. Therefore lumber recovery for the No. 2 & Better group was fit to the regression parameters and then the values of the parameters for the No. 3 & Economy grade group were calculated as complements by construction. Fit statistics for the two groups were computed only for the No. 2 & Better grade group.

[b] Dependent variables were constrained to be between 0 and 1; tobit regressions were fit with these restrictions (SAS 9.2 PROC QLIM with lower and upper bound specifications). A joint Wald test for nonzero coefficients was computed for each regression.

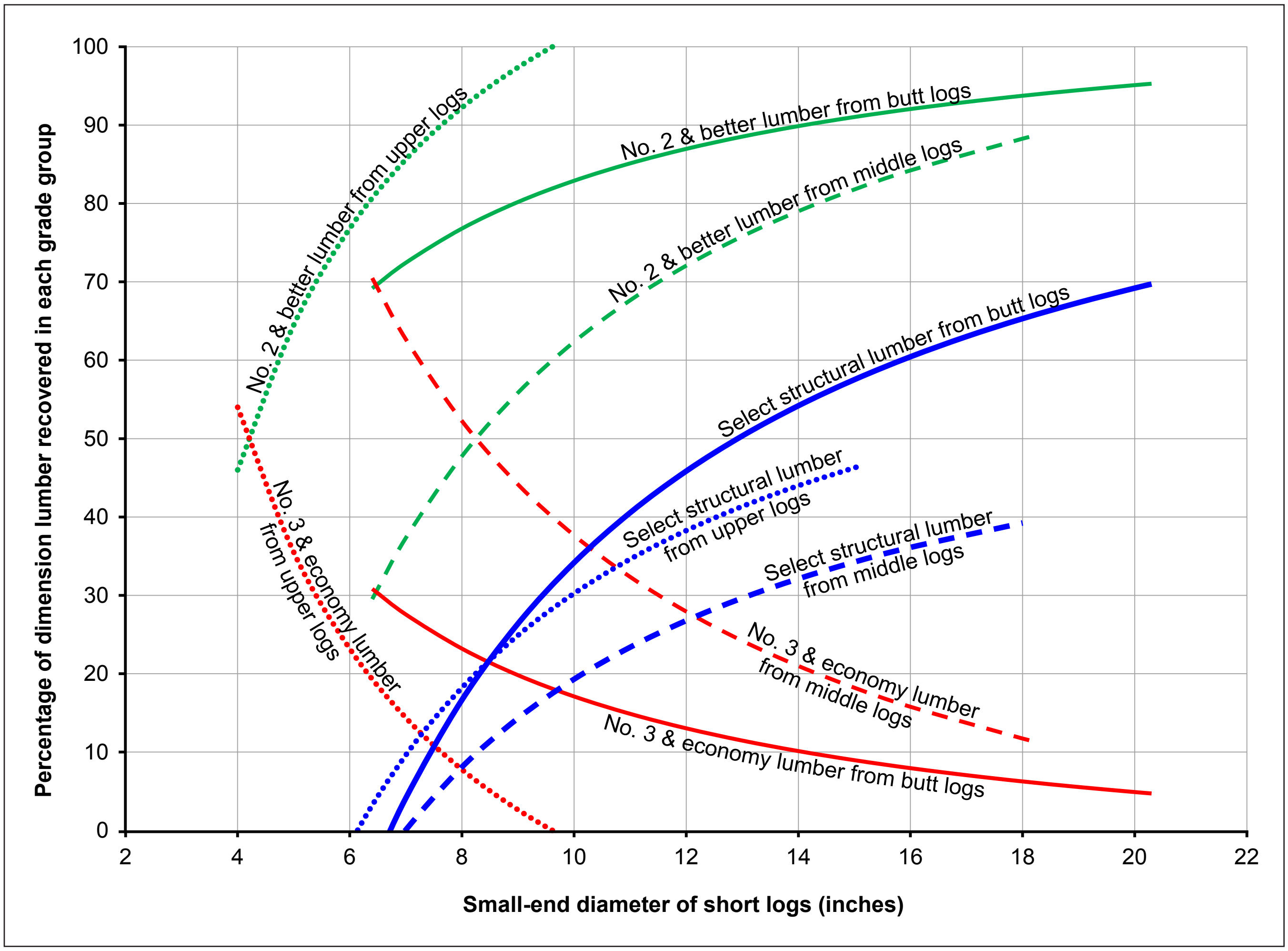


Figure 14—Regression curves showing the percentage of dimension lumber produced from butt, middle, and upper logs from sample trees harvested on Douglas-fir stands in the Oregon Coast Range 15 years after habitat-improvement thinning treatments. Results are shown for each of three grade groupings—Select Structural, No. 2 and Better (Select Structural, No. 1, and No. 2), and No. 3 and Economy (No. 3 and Economy grades).

middle and upper logs, and log length was also significant for upper logs. A higher percentage of live knots tended to increase the percentage of lumber in the higher grades, whereas increased knot diameter had the opposite effect. The log-length parameter in upper logs had a negative sign, indicating that longer upper logs had lower percentages of dimension lumber in the higher grades.

Although the statistical analysis for short logs generally confirmed the relationships that would be expected, the regression equations usually explained less than a third of the total variance in the data. Thus the relationships depicted in figure 14 should only be considered ideals; actual results for any particular sample of logs would likely vary substantially.

Lumber value recovery regression analysis—

The regression model as described in equation (2) was used to fit the data to regression equations for value recovery from trees and short logs in accordance with the following specifications:

- The response variable was defined as the estimated value of lumber recovered, in dollars per hundred cubic feet of gross cubic volume as calculated for the merchandized tree stem or the short log.
- The function of diameter used as an independent variable was defined as the inverse of DBH for tree stems and the inverse of small-end diameter for short logs, both in inches.
- The function of length used as an independent variable was defined as the merchandized stem length for tree stems and log length for short logs, both in feet.

Table 25 summarizes results from the regression analyses for both tree stems and short logs. When compared to other more significant variables, length was not a robust predictor of lumber value recovery for either tree stems or short logs. For tree stems, no random effects were statistically significant. The inverse of DBH and the percentage of live knots in the tree stem were the most significant predictor variables, with average knot diameter and knot density also being significant. Figure 15 shows the effect of DBH on lumber value that was calculated using data from the simulated sawing. The regression equation explained about 60 percent of the variance.

For short logs (table 25), nonconstant variance resulting from the position of the log within the tree was significant and was incorporated into the model. In the fixed-effects analysis, the estimated lumber value was strongly related to the inverse of small-end diameter, knot density, the live-knot fraction, mean knot diameter, and the amount of sweep in the log. Butt logs tend to produce lumber with higher value per cubic foot of log volume than upper logs, as was confirmed by the signs on the regression parameters associated with the B and U dummy variables from equation (2). However, the effect of small-end diameter was modified in upper logs through the U*D interaction variable. As shown in figure 16, upper logs with a given small-end diameter (such as 7 inches) can actually produce higher lumber values per cubic foot than butt or middle logs with the same small-end diameters. This result might seem surprising; but because the butt log normally has the largest small-end diameter, it would typically produce higher value lumber than middle or upper logs from the same tree. Figure 16 also shows average regression values for maximum sweep offset. Sweep was limited to butt and middle short logs in this study, occurring only in 76 of the 324 short logs produced by the bucking simulator.

Table 25—Results of regression analyses on the value of lumber (U.S. dollars per 100 cubic feet) produced from sample trees in Douglas-fir stands on the Oregon Coast Range 15 years after commercial thinning treatments; variables whose parameters were not significantly different from zero at $\alpha = 0.05$ have been excluded

	Overall fit		Parameter estimates for individual variables					
Groupings	**Statistic**	**Value**	**Regression variable**	$\hat{\beta}_j$	**Standard error**	**Degrees of freedom**	t	**p value**
Tree stems	Adjusted R^2-*conditional*	0.595	Intercept	369.57	28.232	61	13.09	< 0.0001
	Adjusted R^2-*marginal*	0.595	D = 1/DBH (inches)	-1,642.41	205.20	61	-8.00	< 0.0001
	RMSE-*marginal*	18.8969	K = Knots per foot	-12.09	5.6562	61	-2.14	0.0366
	Observations	66	LF = Live-knot fraction	55.26	19.030	61	2.90	0.0051
			KD = Mean knot diameter (inches)	-37.74	15.258	61	-2.47	0.0162
			$\hat{\sigma}^2_{\varepsilon} = 386.36$					
Short logs	Adjusted R^2-*conditional*	0.651	Intercept	408.14	13.927	275.3	29.31	< 0.0001
	Adjusted R^2-*marginal*	0.651	D = 1/SED (inches)	-1,231.16	103.18	168.5	-11.93	< 0.0001
	RMSE-*marginal*	30.9604	K = Knots per foot	-14.97	2.7789	261.3	-5.39	< 0.0001
	Observations	324	LF = Live-knot fraction	91.31	10.167	286.2	8.98	< 0.0001
			KD = Mean knot diameter (inches)	-51.89	8.4800	264.5	-6.12	< 0.0001
			B = Butt log	12.91	4.6878	186.9	2.75	0.0065
			U = Upper log	-50.11	13.004	313.4	-3.85	0.0001
			U*D = Upper log*1/SED	269.28	118.75	268.9	2.27	0.0242
			S = Sweep maximum offset (inches)	-11.02	1.9608	154.1	-5.62	< 0.0001
			$\hat{\sigma}^2_{\varepsilon,butt}, \hat{\sigma}^2_{\varepsilon,middle}, \hat{\sigma}^2_{\varepsilon,upper} = (542.10,871.38,1264.25)$ ($p = 0.0006$)					

$\hat{\beta}_j$ = the estimated regression coefficient for variable j, where $j = 0$ for the regression intercept and $j > 0$ for the independent variables in the equation.

t = the "Student's" t-statistic for testing whether $\beta_j = 0$ (may be approximate).

R^2 = the statistical coefficient of determination (adjusted for the number of model parameters, based on either conditional or marginal residuals as determined on the original scale).

RMSE = the square root of the mean squared error (commonly known as "root mean squared error").

DBH = diameter at breast height.

SED = small-end diameter of the log.

$\hat{\sigma}^2_i$ = the estimated variance of random-effect variable i; when $i = \varepsilon$, the variance estimate is for the error term or components of the error term.

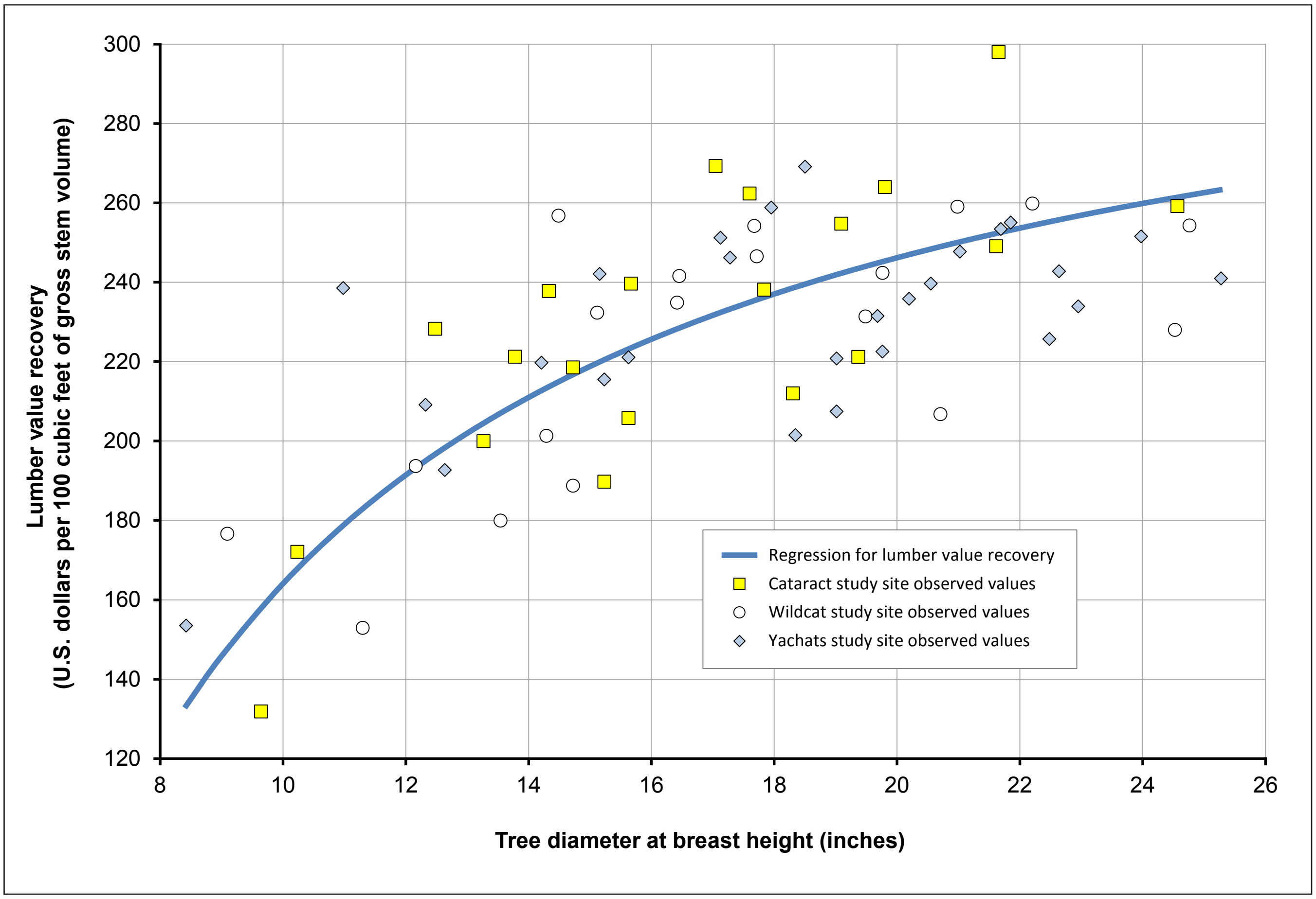


Figure 15—Estimated value of lumber recovered from sample trees harvested on Douglas-fir stands in the Oregon Coast Range 15 years after habitat-improvement thinning treatments.

Thus for butt and middle logs with no sweep (dashed lines in fig. 16), the regression curves are shifted upward compared to those for butt and middle logs with sweep (solid lines), indicating higher expected lumber value recovery for logs without sweep than those with sweep.

Treatment Effects on Stem Profiles and Branch Locations

Sample Size

Following the procedure described in appendix 4, we mapped long-log coordinates for profile points and branch locations into equivalent standing-tree coordinates for all logs from 37 sample trees, for two logs each from 11 three-log trees, and for one log each from four three-log trees and six two-log trees (table 26). Logs from the remaining eight sample trees—of which two were two-log trees and six were three-log trees—could not be mapped because their identifying labels were lost, destroyed, or rendered unreadable. Altogether, profile-point and branch-location

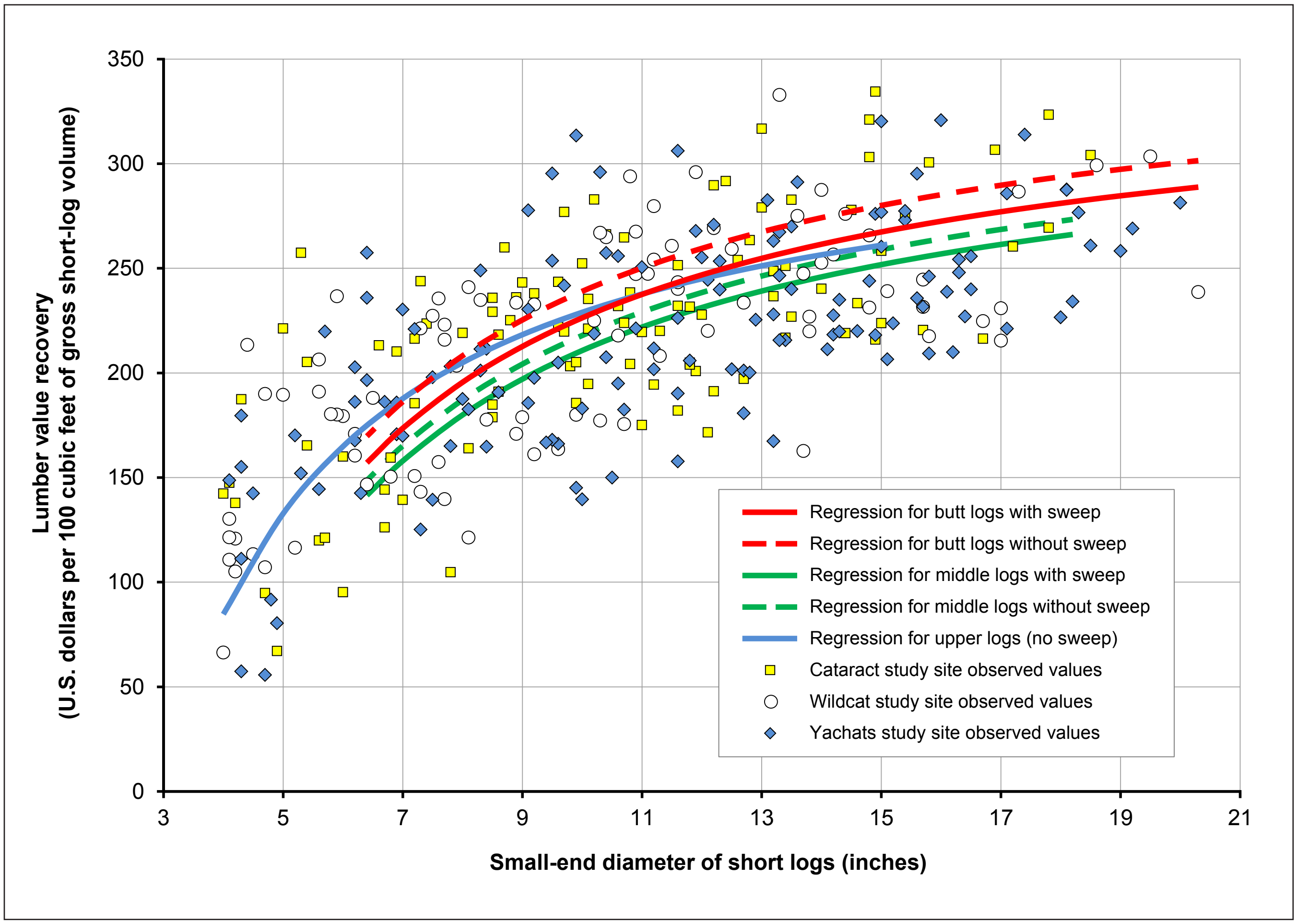


Figure 16—Estimated value of lumber recovered from short logs that were cut from sample trees harvested on Douglas-fir stands in the Oregon Coast Range 15 years after habitat-improvement thinning treatments.

coordinates were available for 132 of the 179 long logs in the study, or 74 percent of the total (table 27). These logs had 75 percent (8,193 of 10,970) of the knots measured in the study.

As shown in tables 26 and 27, the trees and logs with surviving data were not evenly represented among the three sites. All but five of the 47 long logs with missing azimuth data and all eight of the trees with no data were from the Yachats study site—the first site logged using a field procedure that called for painting the top of each felled log with a line and a symbol (N, NE, E, SE, S, SW, W, NW) to indicate the direction toward which the log had faced in the standing tree. After yarding, some indicators were missing or were so badly faded that they had become unreadable. For the Cataract and Wildcat sites, we modified the procedure, replacing painted indicators with tags that were stapled to both ends of each log (fig. 5). This proved to be a much more robust procedure—all but two logs from two trees on the Cataract site and three logs from three trees on the Wildcat site had readable

Table 26—Availability of azimuth data for long logs recovered from sample trees in Douglas-fir stands on the Oregon Coast Range 15 years after commercial thinning treatments; one four-log tree is treated as a three-log tree because its top log was lost and could not be measured

	Data availability for two-log trees			Total two-log trees	Data availability for three-log trees				Total three-log trees
Grouping	No data	One log	Both logs		No data	One log	Two logs	All logs	
All sites	2	6	11	19	6	4	11	26	47
Cataract	0	0	3	3	0	0	2	15	17
Wildcat	0	1	8	9	0	0	2	8	10
Yachats	2	5	0	7	6	4	7	3	20
Treatment T100[a]	1	4	8	13	5	2	6	16	29
Treatment T60[b]	1	2	3	6	1	2	5	10	18

[a] Stand reduced to approximately 100 trees per acre (light thinning).

[b] Stand reduced to approximately 60 trees per acre (moderate thinning).

Table 27—Stems, long logs, and knots with and without azimuth data for sample trees in Douglas-fir stands on the Oregon Coast Range 15 years after commercial thinning treatments

	Total			Azimuth data available						Azimuth data not available					
				Sample trees		Long logs		Knots		Sample trees		Long logs		Knots	
Grouping	Sample trees	Long logs	Knots	Count	Percent	Count	Percent	Count	Percent	Count	Percent	Count	Percent	Count	Percent
All sites	66	179	10,970	58	88	132	74	8,193	75	8	0	47	26	2,777	25
Cataract	20	57	3,058	20	100	55	96	2,971	97	0	0	2	4	87	3
Wildcat	19	48	3,481	19	100	45	94	3,221	93	0	0	3	6	260	7
Yachats	27	74	4,431	19	70	32	43	2,001	45	8	30	42	57	2,430	55
Treatment T100[a]	42	113	6,712	36	86	82	73	4,922	73	6	14	31	27	1,790	27
Treatment T60[b]	24	66	4,258	22	92	50	76	3,271	77	2	8	16	24	987	23

[a] Stand reduced to approximately 100 trees per acre (light thinning).

[b] Stand reduced to approximately 60 trees per acre (moderate thinning).

tags after yarding. As a result, coordinates could be determined for only 45 percent of the knots measured on logs from Yachats, compared to about 95 percent Cataract and Wildcat combined (all but five top logs).

Data on the locations of knots in standing trees can help wood-quality specialists consider how to alter utilization procedures for improved lumber quality. For instance, sawing simulations often assume that knots are uniformly distributed around the bole of the tree. If instead, they follow a less uniform distribution, sawmills could potentially improve lumber quality by modifying the way the logs are initially presented to the saw (Benjamin et al. 2009). In the section below, we present a preliminary analysis of the way knots were distributed around the boles of the sample trees measured for this study. The analysis is limited because we consider only the horizontal distribution of knots around the bole, ignoring the vertical distribution of knots within the tree crown. The intention of this exploratory analysis is merely to demonstrate how a three-dimensional dataset could be used for such evaluations.

Statistical Analysis

As with the mapping of three-dimensional log coordinates, the analysis of the distribution of knots around the boles of standing trees was somewhat more complicated than it might at first seem. By definition, azimuths are inherently circular; an azimuth of 360° is identical to an azimuth of 0°. Given two knots, one with an azimuth of 10° and the other with an azimuth of 350°, the average of the two would be 360° (or equivalently, 0°). Conventional analysis, however, would yield an average of 180°, the arithmetic average of 10 and 350. Such difficulties were overcome by converting the azimuths to unit vectors, with each knot azimuth represented by a vector indicating the direction of the azimuth and having a unit length. Vector arithmetic was then used to derive averages and statistical tests. The set of statistical procedures that has been developed for this purpose is commonly referred to as circular statistics (Fisher 1993, Jammalamadaka and SenGupta 2001).

Figure 17 provides a set of circular histograms that summarize data for the 8,193 observations derived by mapping knot coordinates from long-log measurements into equivalent standing-tree coordinates. In the histograms, the knot azimuths have been aggregated into 10-degree azimuth sectors with histogram bars at the centers of the sectors. A percentage scale was used so that histograms of different sizes could be depicted at the same scale. If all knots were uniformly distributed around the bole of the tree, each bar would be 2.78 percent in length because there are 36 bars, one for each 10-degree sector in the circle (1/36 = 0.0278). Each histogram shows the circular average knot azimuth by site or treatment along with the 95 percent confidence interval for the average.

For the statistical analysis, we used a specialized software package known as Oriana (KCS 2010), which was developed specifically to facilitate analysis of circular data. The null hypothesis was that knots are uniformly distributed around the boles of standing trees. The results, for all data combined and separately by site and treatment are summarized in table 28.

Data analyzed for knots from all sites and treatments combined indicated clustering on the south to southwestern sides of trees rather than a uniform distribution around the boles. Although the results of the three statistical tests for uniformity shown in table 28 were strongly significant, the clustering tendency was relatively modest (fig. 17).

For the three sites individually, the results of the statistical tests suggest that knots on sample trees from the Cataract and Yachats sites were uniformly

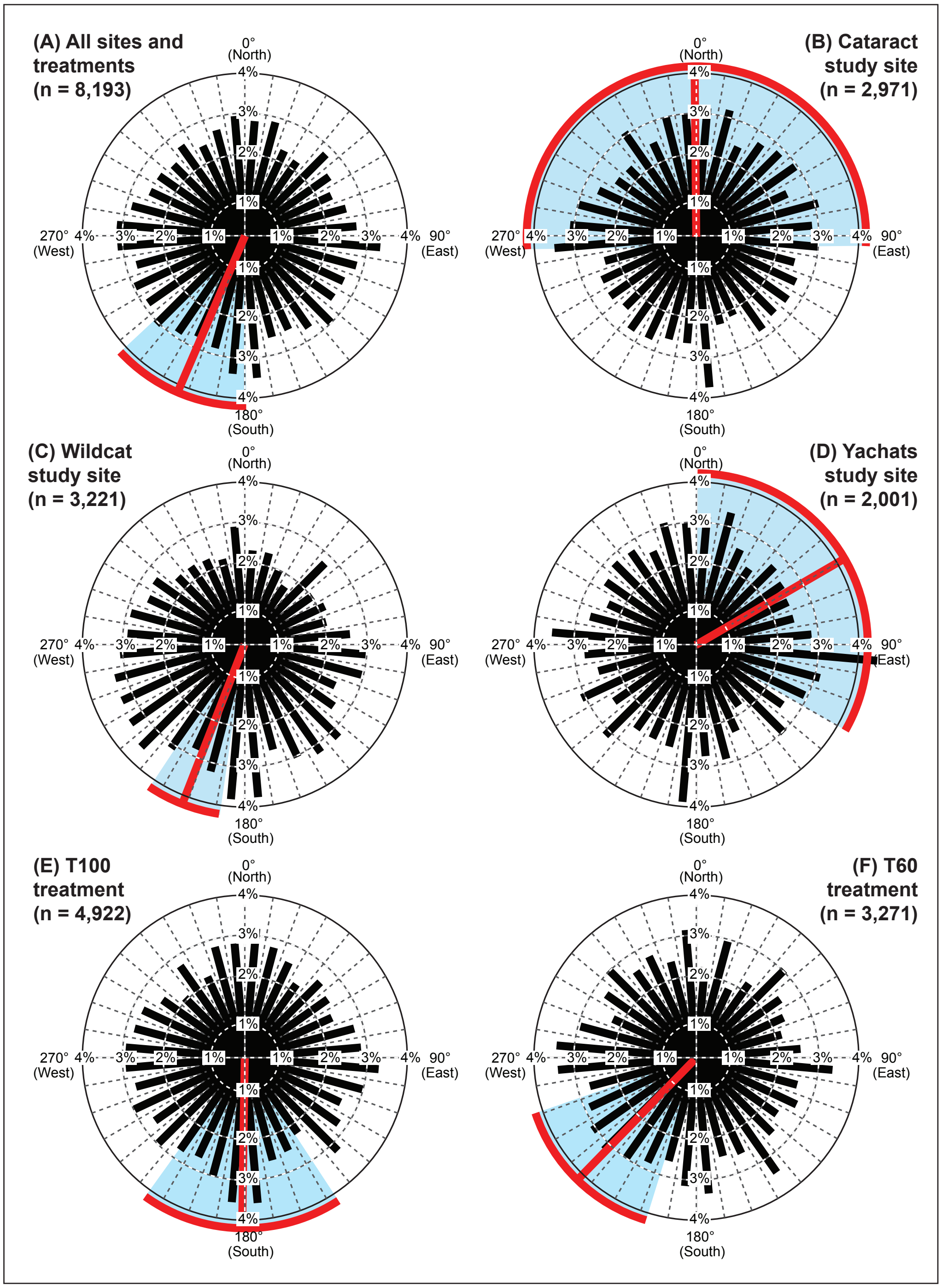


Figure 17—Distribution of knots around the boles—reconstructed as they would have appeared before harvesting—of sample trees harvested on Douglas-fir stands in the Siuslaw National Forest 15 years after two habitat-improvement thinning treatments, the first leaving 100 trees per acre and the second leaving 60 trees per acre: (A) all study sites and treatments totaling 8,193 knots, (B) Cataract study site totaling 2,971 knots, (C) Wildcat study site totaling 3,221 knots, (D) Yachats study site totaling 2,001 knots, (E) the lighter thinning treatment T100 totaling 4,922 knots, and (F) the moderate thinning treatment T60 totaling 3,271 knots. The black bars represent the percentage of knots that faced toward each 10-degree azimuth sector when the tree was standing, the red lines represent the mean azimuth for the knots in each histogram, and the red arcs and associated shading show the 95 percent confidence intervals for the mean.

Table 28—Circular statistics used in analyzing knot-azimuth data for sample trees in Douglas-fir stands on the Oregon Coast Range 15 years after commercial thinning treatments

		Grouped by site			Grouped by treatment	
Statistic	**Total**	**Cataract**	**Wildcat**	**Yachats**	**T100**[a]	**T60**[b]
Number of knot-azimuth observations	8,193	2,971	3,221	2,001	4,922	3,271
Circular mean azimuth, degrees	203.4	359.5	201.5	59.9	181.8	224.2
95 percent confidence interval for the mean:						
Left limit of arc (degrees)	227.1	265.8	214.2	0.6	216.8	251.7
Right limit of arc (degrees)	179.6	93.3	184.8	119.2	146.8	196.7
Length of mean vector (r)	0.037	0.016	0.110	0.006	0.032	0.050
Circular variance	0.963	0.984	0.890	0.994	0.968	0.950
Circular standard deviation (degrees)	147.2	165.4	120.4	183.6	150.1	140.0
Statistical tests for uniformity:						
Rayleigh test (Z)	11.158*[c]	0.717 ns[d]	38.963*	0.070 ns	5.154*	8.321*
Watson's test (U^2)	0.633*	0.069 ns	2.000*	0.059 ns	0.327*	0.452*
Kuiper's test (V)	3.111*	1.310 ns	4.390*	1.322 ns	2.331*	2.340*

[a] Stand reduced to approximately 100 trees per acre (light thinning).
[b] Stand reduced to approximately 60 trees per acre (moderate thinning).
[c] The hypothesis that knots are uniformly distributed around the tree boles is rejected ($p < 0.01$).
[d] The hypothesis that knots are uniformly distributed around the tree boles is not rejected ($p > 0.05$).

distributed around the boles of trees (table 28). All of the sample trees from these two sites were located on north-facing slopes, with circular mean knot azimuths of 359.5° for Cataract and 59.9° for Yachats. In contrast, knots on sample trees from the Wildcat site had a statistically significant tendency to concentrate on the south-facing side of the tree with a circular average knot azimuth of 201.5°.

When knot azimuths were grouped by treatment for all sites combined, the statistical tests suggested that they were not uniformly distributed around the boles but had a larger-than-expected tendency to concentrate on the south-facing sides of the trees—nearly due south for treatment T100, and more southwesterly for treatment T60 (fig. 17).

The mixed results from the statistical tests could mean that multiple factors influence knot distribution around tree boles. For instance, competition from nearby trees or effects from microsite conditions are sometimes more important than knot azimuth considered by itself. In addition, the analysis presented here was simplistic in that it treated all knots equally; both larger knots resulting from larger branches and competition among branches on a single tree can influence the distribution of knots. A more sophisticated analysis might consider factors such as knot height within the crown, competition from crowns of nearby trees, interactions between knot size and azimuth, and differences between dead knots and the live knots that are remnants of living branches.

Discussion and Conclusions

Differences Attributed to Thinning Intensity

Perhaps the most important point to take away from this report is that we found consistent differences, sometimes substantial ones, between the two thinning treatments when we analyzed tree-stem and log dimensions and form, knot size and frequency, lumber volume and grade recovery rates, and lumber value (based on estimated prices of recovered lumber) of both trees and logs. Although not all of the analyses showed significant treatment effects, a measure of tree or log diameter was always statistically significant. Because DBH was found to be significantly larger with more intensive thinning (table 1) and because log diameter is closely correlated with DBH, we conclude that the more intensive treatment (reducing the stand to 60 trees per acre) was superior to the less intensive treatment (reducing to 100 trees per acre) in providing larger diameter trees and larger limbs, thereby improving habitat for nesting and roosting birds such as the marbled murrelet and spotted owl.

Branching—

Trees in the heavier treatment (T60) retained more branches than those in the lighter treatment (T100), possibly because they delayed self-pruning in the more open stands or because they produced epicormic branches to take advantage of increased light availability (Collier and Turnblom 2001). Those branches tended to be larger on average, although our statistical analysis found that branch size was more closely related to stem diameter than to treatment group. Over time, as the residual trees continue to develop, we expect that some of the retained branches will also continue growing and will eventually become suitable for nesting or roosting by the target bird species. Additional thinnings in these stands could accelerate the effect.

Logs—

The more intensive thinning treatment (T60) tended to yield logs with larger diameters and higher average lumber volume, grade, and value recovery. As a consequence, both tree and log values based on estimated lumber recovery were substantially higher on average for treatment T60. Even though the treatment T60 logs tended to have more frequent and larger knots, they also tended to have a higher percentage of live knots (which yield higher lumber grades than dead knots). In addition, the larger diameters of treatment T60 logs resulted in a larger average lumber width as compared to lumber from treatment T100 logs. Because the grading rules for wide pieces are more tolerant of large knots, the net result was larger average value per log.

Juvenile wood—

We were unable to determine whether juvenile wood is influenced by thinning intensity. Previous studies have shown that an increase in the proportion of juvenile wood as a result of increased thinning intensity tends to reduce the value of lumber recovered from residual trees (Barbour and Parry 2001). Because the AUTOSAW simulator does not consider juvenile wood in assigning lumber grades we did not attempt to measure this attribute or incorporate it into our analysis.

Lumber from Simulated Sawing

Results from the simulated sawing indicate that the proportion of lower grade lumber (No. 3 and economy) recovered from the thinning treatments was high—ranging from 24 percent to 30 percent of all lumber produced from the three sites—compared to about 11 percent for all Douglas-fir logs sawn in western Oregon and Washington from 2007 to 2008 (WWPA 2010). The corollary is that the proportion of higher grade lumber (Select Structural, No. 1, and No. 2) was much lower—ranging from 70 percent to 76 percent by site—compared to 89 percent for the Douglas-fir industry as a whole. This means that attracting purchasers for similar thinning operations would likely translate into low stumpage prices for the Forest Service.

The lumber from treatment T60 logs had a much higher estimated value than lumber from treatment T100 logs; this differential, which is mostly the result of larger average piece width, is not a certainty for future valuations. Engineered products like wood I-beams, laminated veneer lumber, and glue-laminated beams continue to make inroads in replacing dimension lumber that is wider than about 8 inches. A question we did not address was whether the differences in knot size and distribution would have affected grade recovery and estimated value if lumber widths had been limited to 6 or 8 inches. Such a constraint would likely have changed the results for grade and value recovery because larger knots are allowed in 10- and 12-inch lumber than in smaller pieces. Limiting sawn pieces to the narrower widths would likely reduce lumber grade yields; should this result in an even higher proportion of No. 3 and economy lumber, revenues from thinnings might not pay the full cost of management activities intended to improve habitat or benefit other ecosystem services. Even though our estimated yield of No. 3 and economy lumber was much higher than the industry average for Douglas-fir logs (WWPA 2010), it was nevertheless more optimistic than earlier projections of 27 to 39 percent for the same thinnings (Barbour et al. 1997). One reason for the difference is that the earlier study modeled lumber grade and volume outputs for the entire residual stand, but we collected morphological data and modeled lumber grade and volume outputs only for a sample of trees actually harvested in the second thinning. Regardless of the reason, the combination of empirical data and model projections in this study present a slightly more hopeful picture than was projected 15 years earlier for the same silvicultural treatment.

Future Research Needs

The research procedures and computer programs developed in this study have provided useful information on the quantity, quality, and potential value of lumber recovered from habitat-improvement thinnings in second-growth Douglas-fir. Even so, the results are constrained by the limitations of the sawing simulator that was used, a computer program developed originally for use in New Zealand and adapted to simulate the production of lumber from second-growth Douglas-fir logs. One shortcoming of the simulator is that it was not designed to consider juvenile wood, an important determinate of lumber grade in wood from second-growth Douglas-fir logs. Thus the results are incomplete because the estimated quality and value yield of lumber produced from the thinnings cannot be verified, even though the results seem reasonable by comparison with industry averages.

One way to improve estimates of lumber quality and quantity from thinnings would be to conduct a full-scale sawmill study in which the lumber produced from sample logs is tallied and then graded by certified lumber graders. Such studies are expensive but provide valuable information that cannot be obtained any other way. The chief disadvantage, other than cost, is that a sawmill study is inherently limited by the characteristics of the specific mill selected to host the study.

A second way to improve estimates of the quality and quantity of lumber yields from habitat-improvement thinnings would be to use a sawing simulator capable of including juvenile wood in its estimation of lumber grade. Several such simulators exist but their cost is high. A potential advantage of using such a simulator is that its cost could be spread over a large number of simulation experiments as compared to the one-time cost of a sawmill study. The data obtained in the current study, for instance, could be used to simulate lumber production under a variety of assumptions about sawmill conditions and technologies. This would provide useful comparisons with the results produced from the AUTOSAW simulations.

The study reported here considers only one aspect of the information needed to effectively manage Oregon coastal forests for the multitude of outcomes that are required from public forests. In particular, because the thinnings that form the basis of the study were designed to accelerate the development of large trees with large branches and other old-growth characteristics that would improve habitat for bird species whose survival depends on such characteristics, research to assess the resulting thinnings from the perspective of wildlife management would be helpful to forest managers who must make decisions about whether to continue this type of thinning program.

Finally, the data collected in this study could be used to improve silvicultural models that consider conditions influencing tree growth, competition among neighboring trees, and development of tree crowns and stem characteristics. The dataset and procedures developed to provide three-dimensional coordinates of stem profiles, branch locations as indicated by surface knots, and surface defects on the stem of each sample tree as it stood before felling could potentially be useful in such research.

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Metric Equivalents

When you know:	Multiply by:	To find:
Inches (in)	25.4	Millimeters (mm)
Feet (ft)	304.8	Millimeters (mm)
Feet (ft)	0.3048	Meters (m)
Miles (mi)	1.609344	Kilometers (km)
Degrees (°)	0.01745329	Radians (rad)
Acres (ac)	0.4046873	Hectares (ha)
Trees per acre (trees/ac)	2.471044	Trees per hectare (trees/ha)
Cubic feet (ft^3)	0.02831685	Cubic meters (m^3)
Board feet (BF) of logs[a]	0.005	Cubic meters (m^3) of logs (approximate)
Board feet (BF) of rough green lumber[b]	0.002071	Cubic meters (m^3) of lumber (approximate)

[a] Conversions between board-foot and cubic-meter log volumes are approximate because of differences in measurement standards and can vary widely from one site to another. For this study the timber cruise volumes were tallied both in board feet and in cubic feet, so the conversion factor shown was derived from the ratio between the board-foot and cubic-foot total cruise volumes (table 2) and the cubic-foot to cubic-meter conversion factor shown above.

[b] Conversions between board-foot and cubic-meter rough green lumber volumes are approximate because of differences in lumber product and measurement standards. The conversion factor shown here was derived by calculating lumber volumes in board feet using nominal lumber dimensions and in cubic feet using actual rough green lumber dimensions, then converting from cubic feet to cubic meters.

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Appendix 1: Program for Checking Software Prerequisites

To run the utility programs that have been developed to organize and prepare data for the Siuslaw Thinning and Underplanting for Diversity Study (STUDS) project, the user's computer must have certain software prerequisites in place. The program described here queries the user's system and reports whether or not the prerequisites required to run the STUDS software have been installed.

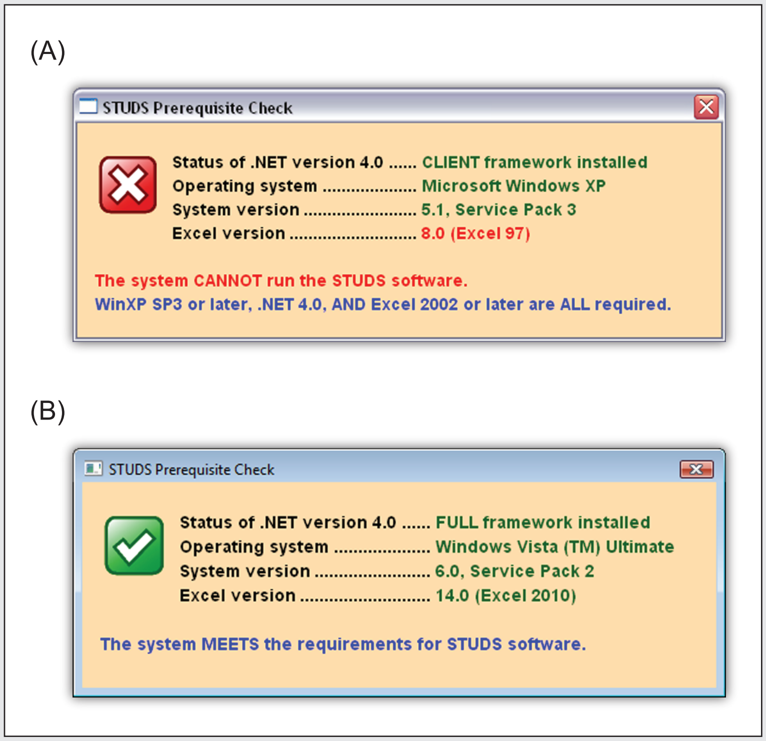
Program Highlights

Executable File: (STUDS_PrereqCheck.exe)—
This file can be copied into any folder on the user's computer without formal installation; administrative privileges are not required.

Requirements—
The program has been designed to run on any computer with Windows 95 or any later version of Windows. There are no other requirements.

Operation—
The user navigates to the folder where the executable file has been placed and double-clicks the filename to launch the program. The program will query the user's computer for the required prerequisites and provide a report such as those shown in figure 18.

Queries Executed—
The program queries the Windows operating system and any service packs that have been installed, the Microsoft .NET Framework version and installation type (client or full installation), and the version of Microsoft Excel that has been installed.



(A)

```
STUDS Prerequisite Check

Status of .NET version 4.0 ...... CLIENT framework installed
Operating system .................. Microsoft Windows XP
System version ..................... 5.1, Service Pack 3
Excel version ....................... 8.0 (Excel 97)

The system CANNOT run the STUDS software.
WinXP SP3 or later, .NET 4.0, AND Excel 2002 or later are ALL required.
```

(B)

```
STUDS Prerequisite Check

Status of .NET version 4.0 ...... FULL framework installed
Operating system .................. Windows Vista (TM) Ultimate
System version ..................... 6.0, Service Pack 2
Excel version ....................... 14.0 (Excel 2010)

The system MEETS the requirements for STUDS software.
```

Figure 18—Results from running STUDS_PrereqCheck.exe software on two different computers: (A) a computer that could potentially run the software if it had a version of Microsoft Excel capable of the type of automation required by the software and (B) a computer that has all the necessary requirements for running the software.

To determine the version of Excel that has been installed on the user's system, the program attempts to automate Excel. This is the same type of automation utilized by the STUDS utility software to read, write, and manipulate Excel files. If Excel is available on the user's system but has not been properly installed and registered under Windows, the query will return a finding of "not installed" because Excel cannot be automated by an external program in that condition.

The STUDS prerequisite checker is a very simple program written in the C++ programming language. It has been explicitly designed to work on any recent version of Windows. It uses only standard Windows programming libraries and has no special runtime requirements. The program displays a single window of the type shown in figure 18. The size of the report window can vary depending on the user's operating system and the results of the prerequisite checks. To close the window, the user simply clicks the X button in the top right-hand corner.

Unblocking the Executable File

Before using this or any of the other STUDS utility software, the executable file should be "unblocked." This can be accomplished by right-clicking the filename in Windows Explorer, choosing the Properties item from the popup menu, and then clicking the Unblock button in the General tab of the property window. If the Unblock button does not appear, unblocking is not required.

Unsupported Versions of Excel

Only Excel 2002 and later versions support the type of automation required by this and the other STUDS utility software. In addition, certain recent versions of Excel do not support automation at all and the query will return a finding of "not installed" if these versions have been installed on the user's computer. This includes Excel Starter, which comes preloaded on some computers and has only limited capabilities. Also, several complete versions of Excel can be installed using a procedure referred to as Click-to-Run. Although these are full versions of Excel, the installation method does not install all components that are necessary for the software to be automated. Installing the same versions of Excel with the standard Windows Installer rather than with the Click-to-Run installer will permit them to be automated.

Antivirus Software

Because the STUDS prerequisite checker queries the user's operating system and the Windows registry, antivirus software on the user's computer can prevent it from running. The user's guide or help file for the antivirus software package should provide a procedure for indicating to the antivirus software that the executable file is trusted and can be allowed to run.

Appendix 2: Log Bucking Simulator

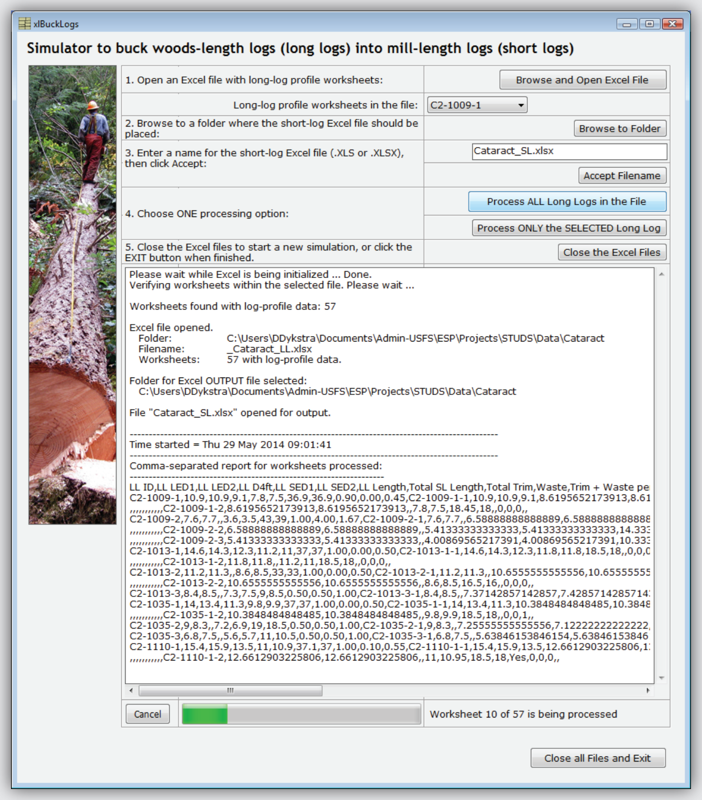
The bucking simulator developed for the Siuslaw Thinning and Underplanting for Diversity Study (STUDS) project, xlBuckLogs.exe, uses relatively simple rules designed to emulate the bucking process typically used by sawmills in western Oregon. This appendix describes the bucking rules used and explains how sweep and crook are treated during the simulated bucking process for long (woods-length) logs.

User Interface for the Bucking Simulator

When the bucking simulator opens (fig. 19), the user browses to an input file by clicking the Browse and Open Excel File button (Step 1) near the top right of the window. If the selected file contains one or more long-log data worksheets in the proper format, a drop-down box immediately below is loaded with the names of all the long-log worksheets in the file. In the image, worksheet C2-1009-1 is shown as the currently selected name in this list. After opening an input file, the user browses to a folder where the output file should be placed by clicking the Browse to Folder button (Step 2). A new folder can be created in this step if desired. After selecting the output folder, the user must enter a name for the output Microsoft Excel file in a textbox (Step 3). If the user’s computer has Excel 2002 or 2003 installed, this filename must have an extension of XLS; for Excel 2007 or later the filename extension can be either XLS or XLSX. The name entered in figure 19 is Cataract_SL.xlsx. When the user clicks the associated Accept Filename button, the new file is created and opened for output.

After the output file has been opened, the user can click either of two buttons (Step 4) to initiate the bucking simulation. One of these buttons processes only the single worksheet currently selected in the drop-down box (the user can change the selection in the drop-down box if desired to choose a different worksheet). The other button initiates the sequential processing of all long-log worksheets in the input file regardless of the current selection in the drop-down box. This is the more normal mode of operation. After the bucking simulation has been initiated it can be interrupted at any time by clicking the Cancel button, located near the bottom left of the window. During the simulation, a progress bar is displayed to the right of the Cancel button with a message indicating the worksheet currently being processed out of the total number of long-log data worksheets in the input file.

The large central part of the window in figure 19 is a text box that provides feedback to the user. Near the top of the text box in the image is information that was displayed when the user browsed to the input file to be opened; it indicates the folder and name of the input file and the number of worksheets in the file that were found to have long-log profile data. Below that is a listing of both the output folder selected by the user and the name of the output file, which the report indicates has been opened for output. The Time Started message near the middle of the text box records the date and time when the user began the bucking simulation. Below the Time Started message is a single line of comma-delimited labels followed by one line of comma-delimited data for each short (mill-length) log produced by the simulation. This report summarizes some of the important long-log inputs and the resulting short-log outputs from the simulated bucking. If desired after the simulation has been completed, this summary report, including the initial line of labels, can be selected with a mouse and copied to the Windows clipboard, then pasted into an empty Excel worksheet as a set of comma-delimited records. This allows the summary report to be formatted in Excel so that the details can be more easily examined. However, this is only an auxiliary report—the main outputs are in the new Excel file created by the bucking simulator. When a simulation has been completed, the user can click the Close the Excel Files button to close both the input and output files and then reset the simulator to process a different input file if desired. Alternatively, the user can click the Close all Files and Exit button to terminate the program.



Simulator to buck woods-length logs (long logs) into mill-length logs (short logs)

1. Open an Excel file with long-log profile worksheets:

Long-log profile worksheets in the file: C2-1009-1

2. Browse to a folder where the short-log Excel file should be placed:

3. Enter a name for the short-log Excel file (.XLS or .XLSX), then click Accept: Cataract_SL.xlsx

4. Choose ONE processing option:

5. Close the Excel files to start a new simulation, or click the EXIT button when finished.

```
Please wait while Excel is being initialized ... Done.
Verifying worksheets within the selected file. Please wait ...

Worksheets found with log-profile data: 57

Excel file opened.
   Folder:        C:\Users\DDykstra\Documents\Admin-USFS\ESP\Projects\STUDS\Data\Cataract
   Filename:      _Cataract_LL.xlsx
   Worksheets:    57 with log-profile data.

Folder for Excel OUTPUT file selected:
   C:\Users\DDykstra\Documents\Admin-USFS\ESP\Projects\STUDS\Data\Cataract

File "Cataract_SL.xlsx" opened for output.

--------------------------------------------------------------------------------
Time started = Thu 29 May 2014 09:01:41
--------------------------------------------------------------------------------
Comma-separated report for worksheets processed:
----------------------------------------------------------------
LL ID,LL LED1,LL LED2,LL D4ft,LL SED1,LL SED2,LL Length,Total SL Length,Total Trim,Waste,Trim + Waste pe
C2-1009-1,10.9,10.9,9.1,7.8,7.5,36.9,36.9,0.90,0.00,0.45,C2-1009-1-1,10.9,10.9,9.1,8.6195652173913,8.61
,,,,,,,,,,,C2-1009-1-2,8.6195652173913,8.6195652173913,,7.8,7.5,18.45,18,,0,0,0,,
C2-1009-2,7.6,7.7,,3.6,3.5,43,39,1.00,4.00,1.67,C2-1009-2-1,7.6,7.7,,6.58888888888889,6.588888888888
,,,,,,,,,,,C2-1009-2-2,6.58888888888889,6.58888888888889,,5.41333333333333,5.41333333333333,14.333
,,,,,,,,,,,C2-1009-2-3,5.41333333333333,5.41333333333333,,4.00869565217391,4.00869565217391,10.333
C2-1013-1,14.6,14.3,12.3,11.2,11,37,37,1.00,0.00,0.50,C2-1013-1-1,14.6,14.3,12.3,11.8,11.8,18.5,18,,0,0,0
,,,,,,,,,,,C2-1013-1-2,11.8,11.8,,11.2,11,18.5,18,,0,0,0,,
C2-1013-2,11.2,11.3,,8.6,8.5,33,33,1.00,0.00,0.50,C2-1013-2-1,11.2,11.3,,10.6555555555556,10.6555555
,,,,,,,,,,,C2-1013-2-2,10.6555555555556,10.6555555555556,,8.6,8.5,16.5,16,,0,0,0,,
C2-1013-3,8.4,8.5,,7.3,7.5,9,8.5,0.50,0.50,1.00,C2-1013-3-1,8.4,8.5,,7.37142857142857,7.428571428571
C2-1035-1,14,13.4,11.3,9.8,9.9,37,37,1.00,0.00,0.50,C2-1035-1-1,14,13.4,11.3,10.3848484848485,10.3848
,,,,,,,,,,,C2-1035-1-2,10.3848484848485,10.3848484848485,,9.8,9.9,18.5,18,,0,0,1,,
C2-1035-2,9,8.3,,7.2,6.9,19,18.5,0.50,0.50,1.00,C2-1035-2-1,9,8.3,,7.25555555555556,7.12222222222222,
C2-1035-3,6.8,7.5,,5.6,5.7,11,10.5,0.50,0.50,1.00,C2-1035-3-1,6.8,7.5,,5.63846153846154,5.63846153846
C2-1110-1,15.4,15.9,13.5,11,10.9,37.1,37,1.00,0.10,0.55,C2-1110-1-1,15.4,15.9,13.5,12.6612903225806,1
,,,,,,,,,,,C2-1110-1-2,12.6612903225806,12.6612903225806,,11,10.95,18.5,18,Yes,0,0,0,,
```

Worksheet 10 of 57 is being processed

Figure 19—The user interface for a log bucking simulator, shown with a simulation underway; the progress bar near the bottom center of the window indicates that the 10th long log from the input file is currently being “bucked” by the simulator.

After the bucking simulation has been initiated, the software either processes the single file selected in the drop-down box or steps sequentially through the entire set of worksheets listed in the drop-down box. For each worksheet, which represents an individual long (woods-length) log to be bucked, the simulator loads all data from Excel into an array, then proceeds as follows:

Step 1. Data Selection

From the first data row of the worksheet, the simulator saves data that are constant for the entire long log. These data include inside-bark diameters at the large and small ends of the log, inside-bark diameter at a point 4 feet from the large end of the log if it is a butt log, length of the log, octant of the longitudinal axis along the top of the log in the 0° orientation, and sweep data if sweep is present in the log.

Step 2. Bucking Simulations

The methodology described below is a generalization of the bucking rules used by several mills that purchased logs from the thinning operations. While processing the first data row, the simulator also determines whether to buck the log and if so, what the resultant short-log lengths should be. For the STUDS project, any long log more than 21.0 feet in length was bucked into two or more short logs. The maximum short-log length for the STUDS project was set as 20.0 feet, maximum trim as 1.0 foot, normal trim allowance as 0.5 feet, minimum short-log length as 8 feet, minimum trim allowance as 0.1 foot, minimum short-log diameter as 4 inches, and increment between short-log lengths as 2 feet. Thus, a log as short as 8.1 feet including trim could be used by the sawing simulator if its small-end diameter was 4.0 inches or larger. Shorter logs would be discarded and sent to a whole-log chipper.

Trimmed lengths of short logs are assumed to occur in even 2-foot multiples. Thus, a short log 11.3 feet long would have a trimmed length of 10.0 feet plus 1.3 feet of trim and waste.

After bucking, any trim in excess of the normal trim allowance of 0.5 foot is considered waste and is discarded. Thus, the length of the log in the example above as used by the sawing simulator would be 10.5 feet including trim, with the additional 0.8 feet of trim being discarded and chipped. Discarded lengths are always removed from the smaller end of the log.

Bucked logs with less than the normal trim are permitted as long as the trim is at least equal to the minimum trim allowance (0.1 foot for the STUDS project). Thus, a bucked log 18.1 feet long is processed as an 18-foot log. Most mills prefer to have more than 0.1 foot of trim, so this allowance is somewhat different from common practice. Some mills would treat an 18.1-foot log as a 16-foot log with 0.5

feet of trim and 1.6 feet of waste. However, the more modern, automated mills are capable of sawing logs with as little as 0.1 foot of trim.

Determining the number of short logs—
For logs longer than 21.0 feet, the procedure outlined below is used by the bucking simulator to determine how many short logs should be cut from any long log. This procedure is not guaranteed to work correctly for all possible situations, but it was adequate for all of the long logs in the STUDS project. The methodology begins by postulating that two short logs will be cut from the long log. It calculates the total length, including trim and waste, of each short log cut from the long log in n equal lengths. The maximum trimmed short-log length and the maximum trim are added together; if the total length of each short log is larger than this sum, the procedure increases n by 1 and total length is recalculated. Otherwise, the current value of n is accepted as the number of short logs to be cut from the long log. The trimmed log length can then be calculated; the method used ensures that the trimmed length is always an exact multiple of I, the increment between trimmed short-log lengths. The amount of trim is calculated and adjusted if it exceeds the normal trim for a short log. The amount of waste, if any, is also calculated.

Initialize $n = 2$

Calculate $L_{SL} = L_{LL}/n$

If $L_{SL} > (L_{T.SL(Max)} + T_{Max})$,increase n by 1 and recalculate $L_{SL} = L_{LL}/n$

If $L_{SL} \leq (L_{T.SL(Max)} + T_{Max})$, accept n as the number of short logs to be cut from the long log

Calculate $L_T = Truncate(L_{SL}) - Modulo(Truncate(L_{SL}), I)$

Calculate $T = L_{SL} - L_T$

If $T > T_{Normal}$, set $W = T - T_{Normal}$; then set $T = T_{Normal}$

If $T \leq T_{Normal}$, set $W = 0$

where:

n = the number of short logs to be cut from the long log,

L_{LL} = the full length of the long log, including trim and waste,

L_{SL} = the full length of a short log, including trim and waste,

L_T = the trimmed length of a short log,

$L_{T.SL(Max)}$ = the maximum acceptable length of a short log after the trim has been removed (20.0 feet for the STUDS project),

T_{Max} = the maximum acceptable trim for a short log (1.0 foot for the STUDS project),

T_{Normal} = the normal trim for a short log,

I = the increment between trimmed short-log lengths,

T = the actual amount of trim on a short log,

W = the amount of waste (excess trim) discarded from a short log,

Truncate(a) = a mathematical function that truncates the value of a (a positive number) to the next lower whole integer—if a is already a whole integer, *Truncate(a)* returns *a*,

Modulo(b, c) = a mathematical function that returns the remainder when b (a positive number) is divided by c, another positive number—the result is 0 if *b* is exactly divisible by *c*.

For the STUDS project it was never necessary to cut more than three short logs from any long log; in fact, only one long log, C2-1009-2, was bucked into three short logs. The long log was 43.0 feet in length. Following the rule described above, it was first cut into two 21.5-foot short logs. Because 21.5 is a larger number than (20.0 + 1.0), n was increased to 3 and the long log was cut into three 14.33-foot short logs. Because 14.33 is a smaller number than (20.0 + 1.0), the solution was accepted with three short logs to be bucked from the long log. The trimmed length was calculated as 14 feet with trim of 0.33 feet for each short log. There was no waste.

Determining minimum diameter and length—

The log-bucking simulator considers the minimum diameter (4 inches) and minimum length (8 feet) of short logs. After the number of short logs to be cut from the long log is determined as shown above, each short log is considered in turn, beginning with the short log cut from the large end of the long log and proceeding toward the small end of the long log. Following is a summary of the procedure that was followed for each short log i in the STUDS project:

(a) Recalculate the total length of short log i: $L_{SL(i)} = L_{T(i)} + T_{(i)}$. Note the absence of allowance for waste; this is because all waste is taken from the small end of the long log rather than being allocated to individual short logs.

(b) If short log i is at the large end of the long log (meaning that $i = 1$), set its large-end diameter to equal the large-end diameter of the long log. Otherwise, set its large-end diameter to equal the small-end diameter of short log i-1; see (d) below.

(c) Determine the distance from the large end of the long log to the large end of short log i, defined as $\sum_{j<i} L_{SL(j)}$, where the index j refers to the short logs that are closer to the large end of the long log than short log i.

(d) Determine the small-end diameter of short log i from the diameters in the set of profile points recorded for the long log. If necessary, interpolate linearly between the two closest adjacent profile points.

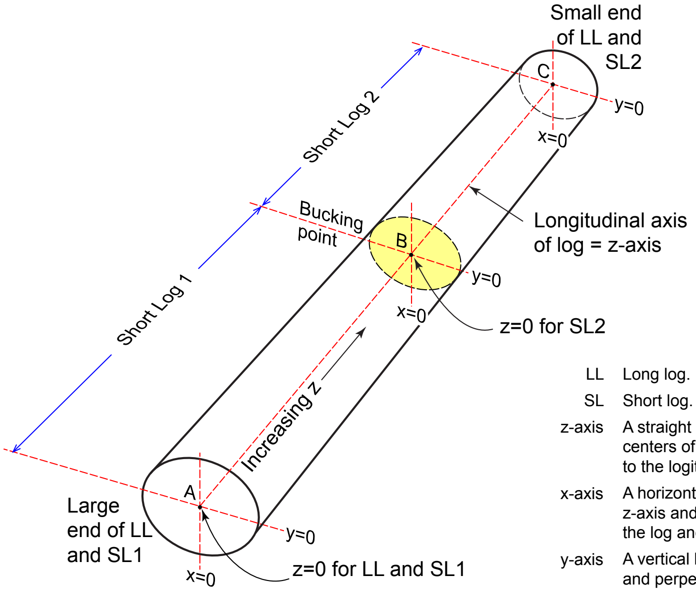
(e) If the small-end diameter determined in (d) above is less than the minimum diameter of 4 inches, reduce the log length by 2.0 feet (I) and determine the new small-end diameter as in (d) above. Continue reducing the length if necessary until you arrive at a feasible small-end diameter.

(f) If the short-log length was reduced in (e) above, compare the new value of L_T with the minimum short-log length (8.0 feet). If the short log is less than this minimum, discard it. Otherwise add the short log and its data to the list of short logs cut from the long log.

Step 3. Correcting Profile Data

Each data row in a long-log worksheet from the input Excel file corresponds to a stem-profile measurement consisting of a distance from the large end of the log to the profile point and the inside-bark horizontal diameter of the log at the profile point. Most rows also include data on surface defects. With the length and position of each short log within the long log determined (step 2 above), the data for each profile point and surface defect can be associated with an individual short log and placed correctly at a specified distance from the large end of the short log. This is handled by simple subtraction as shown in figure 20. Any point on the three-dimensional log image in the figure can be described using x, y, and z coordinates. The x-axis is the reference axis used to measure horizontal log diameters and the y-axis, vertical log diameters. The {0, 0} point where these two axes cross can be found at the geometric center of the log at its two ends and at any point along the z-axis between the two ends. The z-axis runs from the geometric center of the large end of the log to the geometric center of the small end of the log, with z = 0 at the large end. Thus, the z-coordinate at the small end of the log is equal to the length of the log. For a log with no sweep or crook (fig. 20), the z-axis is identical to the longitudinal axis of the log. In the presence of sweep or crook, the longitudinal axis of the log curves away from the z-axis; this is a complicating factor that is further discussed below.

When the long log is bucked into two short logs (SL) as shown in figure 20, any point in the first short log will have the same z-coordinate value as the same point in the long log (LL). However, any point in the second short log will have a different z-coordinate than the same point in the long log because the bucking point (B) becomes the $z = 0$ point for the second short log, whereas in the long log point B has a positive value z_B. The correction for profile points in the second short log is computed as $z_{\mathrm{SL2}} = z_{\mathrm{LL}} - z_{\mathrm{B}}$.



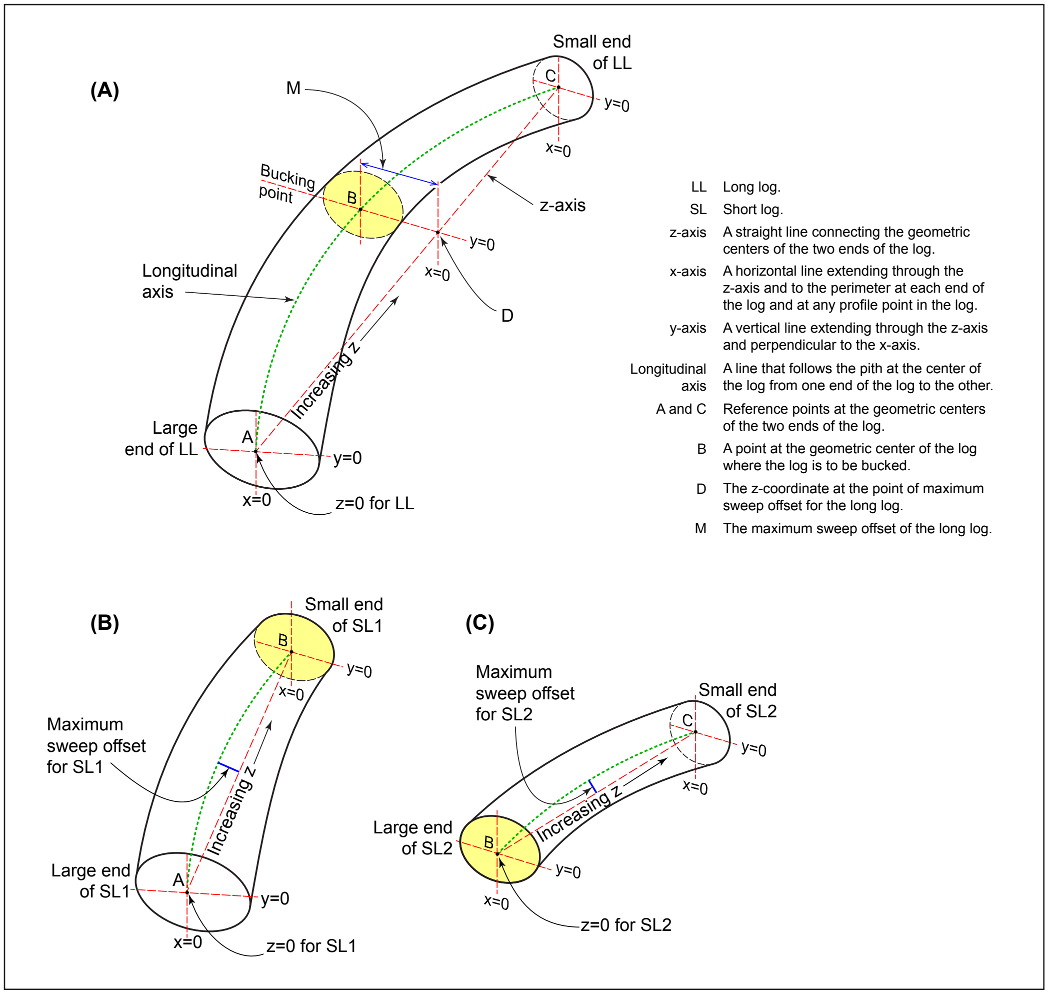
LL	Long log.
SL	Short log.
z-axis	A straight line connecting the geometric centers of the two ends of the log (identical to the logitudinal axis for a straight log).
x-axis	A horizontal line extending through the z-axis and to the perimeter at each end of the log and at any profile point in the log.
y-axis	A vertical line extending through the z-axis and perpendicular to the x-axis.
Longitudinal axis	A line that follows the pith at the center of the log from one end of the log to the other.
A and C	Reference points at the geometric centers of the two ends of the log.
B	A point at the geometric center of the log where the log is to be bucked.

Figure 20—The three-dimensional coordinate system used for simulated bucking of a long log into two short logs; the bucking point shown will become the small end of the first short log and the large end of the second short log.

For logs with sweep, the simple correction described above is an approximation (fig. 21); the z-axis and the longitudinal axis are not identical, with the largest difference occurring at the point of maximum sweep offset. This caused a complication for the STUDS project, because measurements from the large end of the long log to any profile point or surface defect were made along the longitudinal axis of the log rather than directly along the z-axis. However, for all long logs with sweep the maximum difference between any measurement along the longitudinal axis and the corresponding (correct) measurement along the z-axis was never as much as 0.1 foot, which was also the limit of precision for our z-axis measurements, so we ignored the error. Larger errors could be encountered in logs with severe sweep.

Length measurement errors large enough to detect when lengths are measured to the nearest 0.1 foot can occur in logs with a maximum sweep offset larger than about 4 percent of the length. None of the sample logs in the STUDS project had such severe sweep, which is rare because loggers intentionally buck tree stems in ways that reduce sweep—sweep is a scaling deduction and a logger's receipts depend on maximizing the net log scale. If logs with that severity of sweep were encountered, however, the measurement system used in the STUDS project would produce unacceptably large errors for z-coordinates of profile points and surface defects located near the small end of the long log.

Unlike z-coordinates, offsets measured to surface defects from the longitudinal axis as projected along the top of the log are not affected by bucking because the longitudinal axis is the same for the short logs as for the long log. Therefore no correction is needed for offset measurements.



LL	Long log.
SL	Short log.
z-axis	A straight line connecting the geometric centers of the two ends of the log.
x-axis	A horizontal line extending through the z-axis and to the perimeter at each end of the log and at any profile point in the log.
y-axis	A vertical line extending through the z-axis and perpendicular to the x-axis.
Longitudinal axis	A line that follows the pith at the center of the log from one end of the log to the other.
A and C	Reference points at the geometric centers of the two ends of the log.
B	A point at the geometric center of the log where the log is to be bucked.
D	The z-coordinate at the point of maximum sweep offset for the long log.
M	The maximum sweep offset of the long log.

Figure 21—Geometry of sweep in a long log and two short logs bucked from it: (A) the long log being bucked at the point where the sweep offset is at its maximum, (B) the first short log, and (C) the second short log; note that each short log has less sweep than the original long log.

Step 4. Adjusting Sweep Data

Bucking long logs into short logs reduces sweep, as can be seen in figure 21. Each of the two short logs in the figure has substantially less sweep than the original long log. This is because bucking redefines the z-axis in a log with sweep; you can see this by comparing the z-axes for the two short logs with the z-axis for the long log in figure 21. The software used to prepare data files for the sawing simulator requires the position of maximum sweep and the maximum sweep offset for the short logs, so this information must be calculated for each short log as the simulator bucks it from the long log. As noted previously, measurements along the arc of the surface-to-surface defects at any point on the log are not affected by bucking, because the measurements are taken relative to the longitudinal axis along the top of the log and it is the same for the short logs as for the long log. However, for any short log other than the first, the distance from the large end of the short log to the measurement point must be adjusted for the distance between the large end of the long log and the large end of the short log. In figure 21, the z-coordinate of the bucking point is 0 in the coordinate system of the second short log, whereas it has a positive value in the coordinate system of the long log. The bucking simulator makes the necessary adjustments for sweep by using the following procedure:

Locating sweep on short logs—

This requires equations that describe the curve representing the longitudinal axis of the long log and any short logs bucked from it. For our study, we chose to use a parabolic arc with the vertex of the parabola at the point where the maximum sweep offset occurs for the long log (fig. 21). Rather than using a single equation for the long log, we used two; one for arc AB and another for arc BC. This is because the point of maximum sweep may not occur at the center of the long log. To calculate the two parabolic arcs we used the vertex form of the parabola as shown in equation (3). This formulation ensures that the two arcs, AB and BC, will meet smoothly at B, the point of maximum sweep.

As written, the equation assumes that sweep occurs along the x-axis (meaning that the sweep offset is left or right of a straight line drawn between the geometric centers of the two ends of the log, as shown in fig. 21). If instead it occurs along the y-axis (the sweep offset is up or down from the z-axis), the method is the same except that y would be substituted in the equation in place of x.

$$x = (\alpha)(Z - D)^2 + M \tag{3}$$

where:

x = the sweep offset along the x-axis of the long log at any point Z along the z-axis of the long log between Z_{ref} (eq. 4) and D,

α = the parameter of the vertex form of the parabola (eq. 4),

Z = the z-coordinate of any point along the z-axis between Z_{ref} and D as measured from the large end of the long log,

D = the z-coordinate where the maximum sweep offset occurs (in figure 21 this occurs at the bucking point, but in general it could occur at any point along the z-axis),

M = the sweep offset in x- or y-coordinates at point D (the maximum sweep offset)—this value is negative if the sweep direction is down or to the left as viewed from the large end of the log, and positive if the sweep direction is up or to the right.

The parameter of equation (3) is calculated as follows:

$$\alpha = -\mathrm{M} / (Z_{ref} - D)^2 \tag{4}$$

where:

Z_{ref} = the z-coordinate of the reference point for the arc being computed for the long log in figure 21: the z-coordinate at point A (normally 0) if equation (3) is for the arc AB, or the z-coordinate at point C if equation (3) is for arc BC.

Note that the maximum sweep offset (M) for the long log in in figure 21 is negative because the sweep is to the left of the z-axis as viewed from the large end of the log. As a result the value of α calculated in equation (4) will be a positive number for the situation of figure 21. In general, when the sweep is to the left or downward, α will be a positive number; when the sweep is to the right or upward α will be a negative number.

Estimating maximum sweep offset for short logs—
The bucking simulator uses the following iterative procedure to do this for each short log:

(a) Calculate an equation for the straight line joining the centers of the two ends of the short log. This is the z-axis, shown as a dashed line labeled "Increasing z" for each of the two short logs (fig. 21).

(b) Calculate an equation for the straight line perpendicular to the z-axis determined in (a) above.

(c) Set the initial value of the short-log sweep offset to 0. This corresponds to the offset at the large end of the short log, where the z-coordinate = 0.

(d) Set the first calculation point at a distance of 500 mm (19.7 inches) from the large end of the short log as measured along its z-axis. This is an arbitrary distance, chosen to be somewhat less than the value of the increment between trimmed short-log lengths (I); I = 2 feet for the STUDS project.

(e) Calculate the long-log sweep offset corresponding to the current z-coordinate using the model of equations (3) and (4).

(f) Using the geometric relationship between the z-axis of the long log and the z-axis of the short log, together with the equation calculated in (b) above, determine the short-log z-coordinate corresponding to the current point and the distance from the longitudinal axis to the z-axis. This is the sweep offset for the short log at the current z-coordinate.

(g) Compare the short-log sweep offset with the largest previously determined short-log sweep offset. If the new value is higher, save the value of the offset and the corresponding short-log z-coordinate. Then increase the z-coordinate of the long log by 500 mm and go to (e) above. Otherwise, accept the largest previously determined short-log sweep offset as the maximum value; record this value and the corresponding short-log z-coordinate, and terminate the procedure.

This methodology finds the z-coordinate of the maximum sweep offset within a precision of 500 mm for the long log and slightly more than 500 mm for the short log, depending on the severity of sweep. If more precision is needed, a smaller step length or an optimizing procedure such as successive halving (binary search) could be used.

Calculating arc length—

The equation for a parabola has a closed form solution for determining the arc length between any two points on the curve. The sweep-adjustment procedure outlined above does not require the arc length, but knowledge of this value can be useful in determining whether errors resulting from the measurement of z-coordinates along the longitudinal axis of the log (rather than along the z-axis) are large enough to warrant corrections. As mentioned before, the errors in the STUDS project could be ignored because the largest possible error was found to be less than the precision of the original measurements. Logs with more extreme sweep, however, could have larger measurement errors. For a parabola defined as in equations (3) and (4), the arc length between points z_1 and z_2 can be determined as follows (Pahikkala 2009):

$$L=\frac{1}{4\alpha}\left(2\alpha\cdot|z_1-z_2|\cdot\sqrt{(4\alpha^2(z_1-z_2)^2+1)}+\sinh^{-1}(2\alpha\cdot|z_1-z_2|)\right) \qquad (5)$$

where:

L = the arc distance between points z_1 and z_2,

α = the parameter of the parabola computed as in equation (4).

One caveat is that the z-coordinates and value of M used in calculating α in equation (4) must be in identical units of measure for α to be used in equation (5). If z_1 and z_2 are measured in feet, M must also be measured in feet; mixing the units of measure will yield an incorrect result for the arc length.

Step 5. Adjusting Crook Data

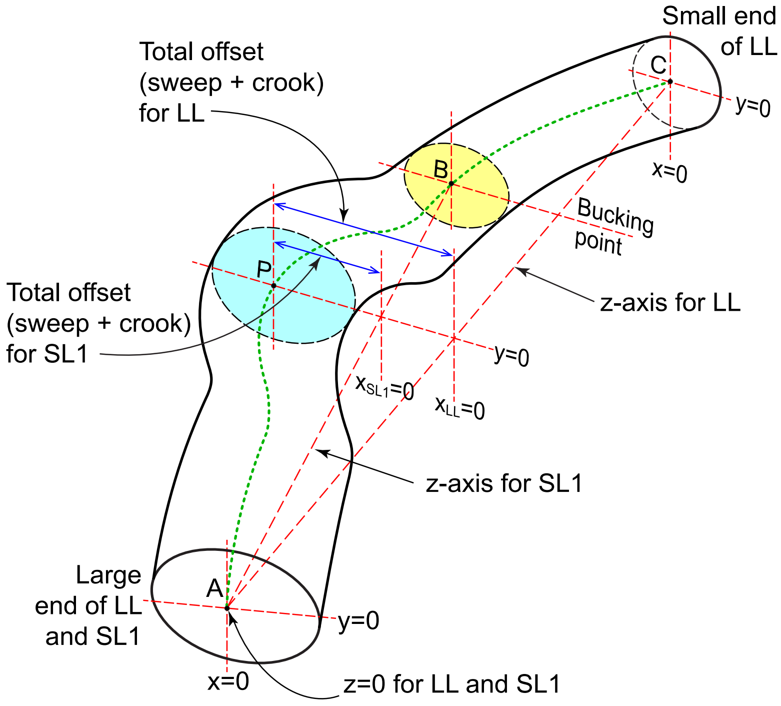
Crooks are similar to sweep in that they cause the longitudinal axis of the log to deviate from the z-axis of the log; they differ in that they do not extend over the entire length of the log. A single log can have more than one crook, a situation that did not occur in the STUDS project. In adjusting the crook offset for a short log, three possibilities must be considered:

Logs without sweep—
No adjustment of the crook offset is necessary, because the z-axis for the short log is the same as the z-axis for the long log. Crook offsets are measured from the z-axis. For short logs other than the first short log bucked from the long log, however, the z-coordinate at the offset point must be adjusted as described in step 3 above.

Logs with sweep—
The crook offset must be adjusted to account for the difference in sweep between the long log and the short log. In the situation shown in figure 22, the crook offset for the first short log is less than the crook offset for the long log. The difference can be calculated by similar triangles, given that the offset from the z-axis of the short log to the bucking point has been calculated as described in step 4 above. For a crook located in the second short log, the procedure is essentially the same but with some modifications required by the slightly different geometry.

Logs with other complications—
A more complicated situation arises if the bucking point occurs within the crook, causing the crook to be split across two short logs and requiring a more complex set of adjustments. For the STUDS project that situation did not occur so we did not attempt to develop a procedure that would incorporate the necessary adjustments.

When both sweep and crook are present in a single long log, the adjustment for sweep is first made as described in step 4 above. Accounting for crook then represents an additional modification to the longitudinal axis of the log, which in turn affects the three-dimensional coordinates of any surface defects that occur along that section of the log. This adjustment is not made by the bucking simulator but must be incorporated later when the three-dimensional data for the short log are determined in preparation for the sawing simulation. The bucking simulator simply stores the crook data—with the z-coordinate and crook offset adjusted as described in step 5 above—in the data worksheet for the short log where the crook occurs.



LL	Long log.
SL	Short log.
z-axis	A straight line connecting the geometric centers of the two ends of the log.
x-axis	A horizontal line extending through the z-axis and to the perimeter at each end of the log and at any profile point in the log.
y-axis	A vertical line extending through the z-axis and perpendicular to the x-axis.
A and C	Reference points at the geometric centers of the two ends of the long log.
B	A point at the geometric center of the log where the long log is to be bucked.
P	Reference point at the center of the crook.

Figure 22—The three-dimensional coordinate system for a short log that was bucked from a long log with both sweep and crook; note that the center of the crook is located at point P between the large end of the long log (A) and the bucking point (B). Although this image shows sweep and crook bending in the same direction, in an actual log they might bend in different directions.

Appendix 3: AUTOSAW

AUTOSAW, the program used to simulate the conversion of short (mill-length) logs into lumber for the Siuslaw Thinning and Underplanting for Diversity Study (STUDS) project, requires log data to be organized as shown in table 29. Each log to be sawn requires a single data file, which is a text file with a filename extension of DAT. The file must provide data on profile points, branch whorls and the individual branches within each whorl, and pith locations for the log to be sawn. Three-dimensional coordinates must be specified in millimeters according to the coordinate system shown in figure 9. The coordinates are measured along the horizontal (x) and vertical (y) axes for any cross section of the log. These coordinates are determined with respect to the initial (0°) orientation of the log. The z-coordinates are measured along an axis running from the geometric center of the large end of the log to the geometric center of the small end. For the STUDS project, z-coordinates always represent distances along the z-axis as measured from the large end of the log.

Data items in an AUTOSAW DAT file (table 29) are delimited by one or more blank spaces or by newline characters. Multiple contiguous delimiters are ignored. The data are divided into the four blocks described below.

Log ID—

The identifier of the short log is entered on the first line of the file; thus the data in table 29 refer to log Y2-1202-1-1. The log ID is preceded by an asterisk, which indicates that the file includes data for individual branches based on measurement of surface knots. This is the only format supported by AUTOSAW that will produce lumber under the U.S. grading rules for Douglas-fir lumber. Without the preceding asterisk, AUTOSAW would expect data in a different format and the output would only be compatible with the New Zealand lumber grading rules for which AUTOSAW was originally developed.

Profile data—

The second block of data describes the log profile. Up to 40 profile points can be entered in the format shown in table 29. Data in this block must be sorted in ascending order according to the z-coordinate, and z-coordinates in adjacent rows of the data file must differ by at least 1 mm. The series of negative x-coordinates in the set of profile points in table 29 indicates that the log profile sweeps to the left as viewed from the large end of the log, similar to what is shown in figure 9. The maximum sweep offset for the short log in table 29 as calculated by the bucking simulator (app. 2) is 78 mm, or 3.1 inches, and it occurs at a distance of 3200 mm (10.5 feet) from the large end of the log. The total length of the log is 5639 mm, or 18.5 feet,

Table 29—Format of an AUTOSAW DAT file with data for one of the short logs from sample trees in Douglas-fir stands on the Oregon Coast Range 15 years after commercial thinning treatments

AUTOSAW DAT file contents[a]	Description
*Y2-1202-1-1	Short-log identifier. The preceding asterisk indicates that branch data are provided.
10	Number of profile points (cannot be more than 40).
0 0 0 245 232 90	Profile points:
-51 0 1219 225 225 0	• The first three numbers in each row are x, y, z coordinates (mm).
-71 0 2073 215 215 0	• The fourth number in each row is the radius of ellipse major axis (mm).
-73 0 2195 212 212 0	• The fifth number in each row is the radius of ellipse minor axis (mm).
-78 0 3200 207 207 0	• The sixth number in each row is the angle of the ellipse major axis (degrees) as measured in a counterclockwise direction from the positive x-axis. Note that for the first profile point this value is 90, indicating that the major axis of the ellipse is oriented along the y-axis (meaning that the log's vertical diameter at that point is larger than its horizontal diameter). For all other profile points the major axis is oriented along the x-axis.
-66 0 4023 203 203 0	
-29 0 5090 189 189 0	
-26 0 5151 192 192 0	
-25 0 5182 191 191 0	
0 0 5639 188 188 0	
5	The number of branch whorls in the log (cannot be more than 48).
-71 0 2073 1	Data for whorl 1: x, y, z coordinates and number of branches (last digit; cannot be more than 12 per whorl but multiple whorls can have the same z-coordinate).
172 2.07 8 0.00 43	Data for branch 1 of whorl 1: 172 = length of the live portion of the branch as measured from the pith toward the log surface (mm). 2.07 = angle to the center of the branch about the central axis of the log as measured from the positive x-axis (radians). 8 = mean radius of the surface knot (mm). 0.00 = rake angle of the branch (radians); 0.00 indicates that the branch is perpendicular to the longitudinal axis of the log. 43 = length of the dead portion of the branch as measured from the top of the embedded live portion of the branch to the log surface (mm).
-73 0 2195 1	Whorl 2 has 1 branch.
170 3.93 22 0.00 42	Data for branch 1 of whorl 2.
-78 0 3200 1	Whorl 3 has 1 branch.
166 3.95 6 0.00 41	Data for branch 1 of whorl 3.
-660 4023 3	Whorl 4 has 3 branches.
204 3.80 10 0.00 0	Data for branch 1 of whorl 4. This branch was recorded as having a live surface knot, so the live length is 204 mm and the dead length is 0 mm.
163 2.84 10 0.00 41	Data for branch 2 of whorl 4.
163 0.04 10 0.00 41	Data for branch 3 of whorl 4.
-270 5144 4	Whorl 5 has 4 branches.
151 2.78 20 0.00 38	Data for branch 1 of whorl 5.
153 2.15 15 0.00 38	Data for branch 2 of whorl 5.
153 3.89 10 0.00 38	Data for branch 3 of whorl 5.
152 -0.83 9 0.00 38	Data for branch 4 of whorl 5.
2	Number of pith coordinates (cannot be more than 60)[b].
0 0 0	x, y, z coordinates of the pith at the large end of the log.
0 0 5639	x, y, z coordinates of the pith at the small end of the log.

[a] Data entries are delimited by a space or return key and multiple contiguous delimiters are ignored by AUTOSAW.

[b] The number of pith coordinates is always 2 for this study, with one set of coordinates located at each end of the log. Intermediate pith locations are assumed to lie along the longitudinal axis of the log, at the geometric center of the log cross-section at each profile point.

inclusive of sawmill trim. AUTOSAW will treat it as an 18-foot log with 6 inches of trim at the small end of the log.

Branch data—

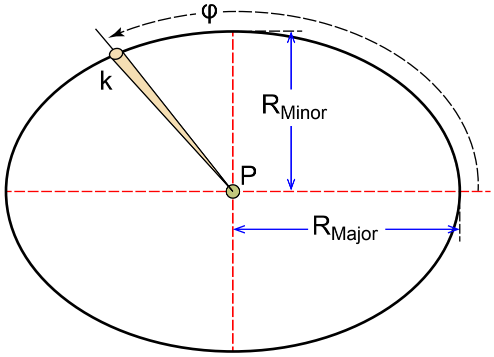
The third data block describes branch data for the log as determined from surface knots. AUTOSAW assumes that each branch is associated with a whorl. A log can have as many as 48 whorls, and each whorl can have up to 12 branches. For the STUDS project, we assumed that a whorl consisted of all branches located within 100 mm (about 4 inches) of each other as measured along the z-axis. The z-coordinate of the whorl was taken to be the arithmetic average of the z-coordinates of all the branches within the whorl.

The data entered for each branch are also described in table 29—see the detailed explanation for the data of branch 1 in whorl 1. Note that the lengths of the live and dead portions of the branch are provided. For the STUDS project, we measured only surface knots and therefore have no information on the live and dead lengths of each branch embedded within the log unless the knot was recorded as a live knot; then the entire branch was recorded as alive and the length of the dead portion was recorded as zero. Following the practice used in previous studies of Douglas-fir sawing with AUTOSAW (Todoroki et al. 2005), we assumed that 80 percent of the length of any embedded branch corresponding to a dead surface knot is alive. The live portion begins at the pith and extends 80 percent of the distance to the surface of the log; the final 20 percent of the embedded branch is assumed to be dead.

The position of each branch is entered as an angle in radians measured from the positive x-axis of the log profile at the branch (fig. 23). This angle is calculated based on the measured position of the knot on the surface of the log under the assumption that the branch grows from the pith and that the pith is located at the geometric center of the log cross section at the branch. For the STUDS project, we assumed that the rake angle of each branch was 0° from horizontal, implying that the branches grow out horizontally from the standing tree. This assumption simplifies certain calculations and is consistent with previous studies that involved simulated sawing of Douglas-fir with AUTOSAW. However, a more sophisticated model would likely vary the rake angle according to the position of the branch within the tree crown.

Pith data—

The final section of the DAT file defines the location of the pith. For the STUDS project we included only two sets of pith coordinates for each log—those for the



k	Surface knot.
P	The point in the pith from which the branch grew.
φ	Branch angle (expressed in radians), always measured counterclockwise from the horizontal axis.
R_{Major}	The radius of the major axis of an ellipse representing the cross-section of the log.
R_{Minor}	The radius of the minor axis of an ellipse representing the cross-section of the log.

Figure 23—Geometry of the log cross section at an arbitrary profile point as defined in AUTOSAW; note that the ellipse shown here has its major axis oriented horizontally but AUTOSAW permits it to be oriented at any angle (orientation is specified individually for each profile point).

large end and those for the small end. The location of the pith is used by AUTOSAW to locate and calculate the size of internal knots based on the branch angle and the average radius of each surface knot. Given that we did not deconstruct each log and thus could not determine the exact location of the pith at each profile point, we simply assumed that the pith was located along the longitudinal axis of the log (at the geometric center of the log cross sections corresponding to the set of profile points).

Short Log Data Conversion

Conversion of data from short-log Microsoft Excel files into the format required by AUTOSAW was accomplished for the STUDS project with a program written in the C# programming language and using Excel automation in the same way as the bucking program described in appendix 2. Following is a brief description of the data-conversion program:

Executable file (xlAutosawDAT.exe)—
Like the bucking simulator, this file can simply be copied into any folder on the user's computer without formal installation; administrative privileges are not required. The user's computer must meet the same requirements as for the bucking simulator (app. 2), and the executable file may need to be unblocked before first use (app. 1).

Supporting file (LogDataFmt.xml)—
This file must be present in the same folder as the executable file. It is identical to the file of the same name used with the bucking simulator (app. 2).

Operation—
The user navigates to the folder where the executable file has been placed and double-clicks the filename to launch the program. The user interface for this program is similar to the one for the bucking simulator (app. 2).

Input file—
This is an Excel spreadsheet file with a filename extension of either XLS (Excel 2002 or 2003) or XLSX (Excel 2007 or later). The file must contain one or more short-log data worksheets that conform to the format described in LogDataFmt.xml. Each short-log data worksheet must be named in the format Aw-xxxx-y-z, where A = a single letter representing the site; w = a single digit signifying the treatment (in the STUDS project; 2 represents the light-thinning treatment T100 and 3 represents the moderate-thinning treatment T60); xxxx = a four-digit tree number; y = a single digit representing the index of the long (woods-length) log from which the short log was cut; and z = a single digit representing the index of the short log (1 = the short log cut from the large end of the long log; 2 = the next short log cut from the same long log; and so on).

Output file—
For each short log to be sawn (represented by a short-log data worksheet in the input file), a text file having the format described in table 29 is written to a folder specified by the user. The filename extension is always DAT, as required by AUTOSAW. Because AUTOSAW was written for the MS-DOS® operating system that predated Windows, the main part of the output filename can be no more than 8 characters in length. However, a short-log name as used in the STUDS project was 11 characters long, including several hyphens. To observe the name-length limit while fully identifying each short log, we specified a separate folder for each site. Because tree numbers within each site were unique regardless of the treatment, this permitted the first three characters of each short-log name to be dropped so that the remaining characters could be used to form the output filename. As an example, the AUTOSAW data for short-log C2-1009-2-3 were written to a file named 1009-2-3.DAT that was created in a folder named C_DAT.

AUTOSAW Simulation Processing

The AUTOSAW sawing simulator (FRI 1994) is proprietary software that was used for the STUDS project under license from Scion, the New Zealand Forest Research Institute. Its use for the STUDS project corresponds to step 5 in figure 8. AUTOSAW was developed for the MS-DOS® operating system, a command-line system that has been supplanted by the Windows graphical-interface operating systems. Current versions of Windows retain the ability to run MS-DOS® programs in a command window opened with the Windows **cmd.exe** processor. However, because of security issues, Windows Vista and later versions prevent the execution of MS-DOS® programs that use full-screen graphics. This is an issue with AUTOSAW, which was designed to use full-screen graphics to display each log as sawing is being simulated. For the STUDS project, we installed Microsoft Hyper-V on a computer running Windows 8.1. Hyper-V is an optional component of 64-bit versions of Windows 8 or later that permits secondary operating systems to run in a protected window. We could then install Windows XP as a secondary operating system under Hyper-V. Because Windows XP permits MS-DOS® programs to use full-screen graphics, we were thus able to run AUTOSAW in the Hyper-V window.

Sawing Strategies

AUTOSAW can implement either of two sawing strategies: cant sawing or live sawing. The two strategies are illustrated in figure 24, which shows the simulation results for a single log sawn both ways. Some pieces of lumber cut from the log are shorter than the trimmed length of the log (18 feet) because AUTOSAW accounts for taper as defined by the set of profile points entered into the DAT file (described above and illustrated in table 29). Only the large-end and small-end diameters are shown in the figure; although the intermediate profile points have been omitted for clarity, they also influence lumber production. Following is a brief description of each sawing method as applied to the specific log shown in the figure.

- For the cant sawing strategy, an initial cut (cut 1) was made to remove the top slab (fig. 24). Then a 1-inch piece was removed in cut 2 immediately below the slab so that most of the cant would lie inside the cylinder defined by the small-end diameter of the log. The log was then turned 180° and a cut made to remove the bottom slab (cut 3). This was followed by removal of an additional 1-inch piece in cut 4. The log was then turned 90° and another slab (cut 5) was removed. This exposed the cant, which was cut into the pieces numbered 6 through 11 by the AUTOSAW simulator. One piece (cut 11) was converted into two pieces with different lengths by the simulated edging process to adjust for log taper. The total volume recovered from the two 1-inch boards and seven 2-inch pieces was 149.33 board feet.
- For the live sawing strategy, an initial cut (cut 1) was made to remove the top slab. Then a series of 2-inch cuts (2 through 5) was made to remove pieces until the center of the log was reached, after which the log was turned 180° and the bottom slab was removed (cut 6). This was followed by a series of cuts made to remove the pieces numbered 7-11. Although pieces from the latter series were all 1-inch boards in this study, the cuts could

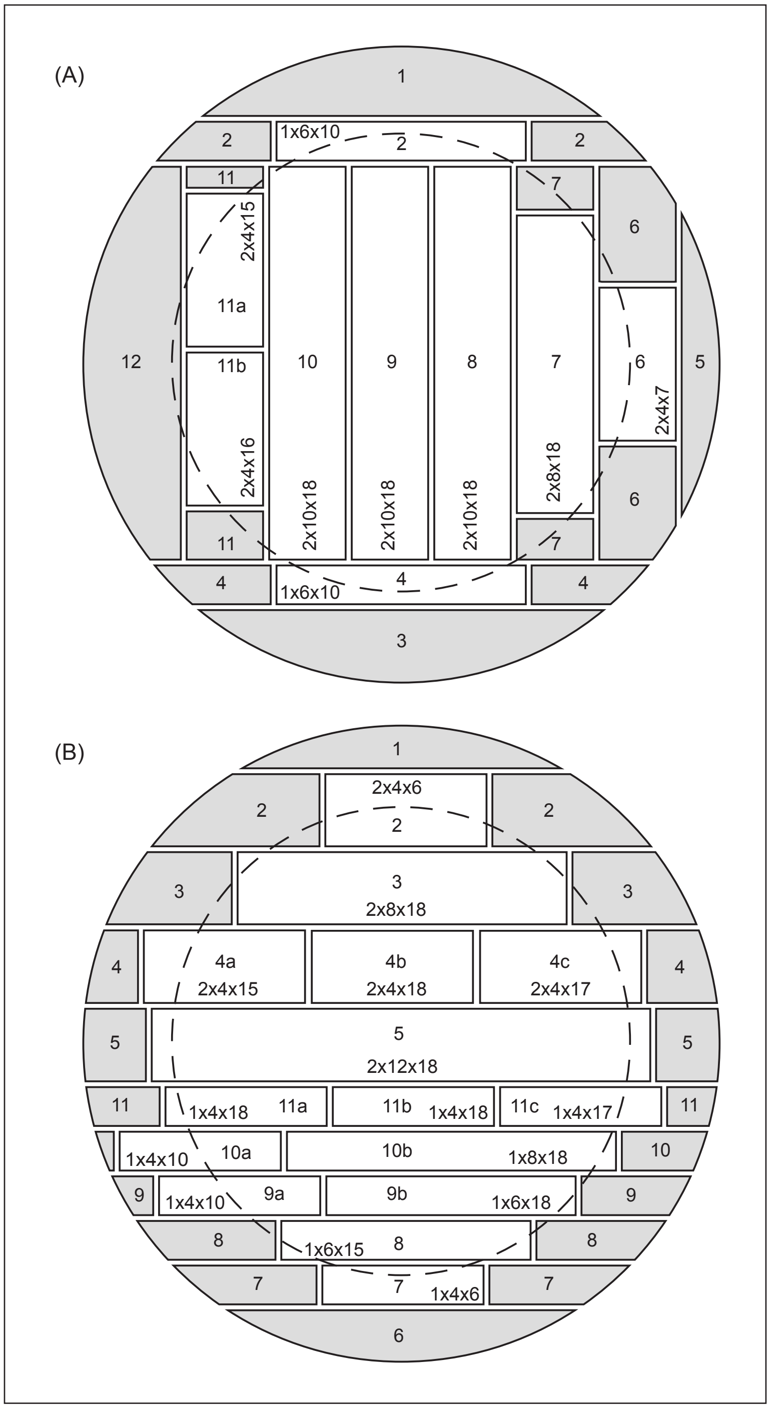


Figure 24—Comparison of AUTOSAW results for lumber produced by (A) cant sawing and (B) live sawing. Saw kerfs are shown as gaps between pieces; pieces discarded by the edger or as slabs are shaded gray; lumber produced by the sawing simulator is white; the solid outside ellipse defining each image represents the large-end diameter of the log; the dashed inner ellipse represents the small-end diameter; and the index numbers within each image indicate the order in which cuts were made by the sawing simulator—with sub-index values (such as 11a, 11b) indicating that a single sawn piece was cut into multiple pieces by the edger.

have been spaced differently to produce dimension lumber. Altogether, four cuts were converted into multiple pieces with unequal lengths by the simulated edging process to adjust for log taper. The total volume recovered from the nine 1-inch boards and six 2-inch pieces was 152.17 board feet.

For this study we elected to use cant sawing for two reasons. First, all previous North American studies using AUTOSAW with unpruned Douglas-fir logs have used cant sawing (Barbour et al. 1997, 1999; Barbour and Parry 2001; Todoroki et al. 2005). Second, cant sawing more closely resembles the cutting strategy commonly employed by sawmills using timber from the Siuslaw National Forest. During a typical shift, however, an individual sawyer would be just as likely to employ both cant and live sawing as well as any of several other strategies. The optimal sawing method can vary from one log to the next (Blackwell and Walker 2006).

AUTOSAW Files

In addition to a data file for each short log to be sawn as described above, the sawing simulator requires the main executable file and several supporting binary files, a set of auxiliary files, a parameter file, and a command file (described below).

Executable file (AUTOSAW.EXE)—

Because this is an MS-DOS® program, it can be installed simply by copying the executable file and several other required files into a folder on the hard drive. We installed the executable file in a folder named C:\Autosaw in the file system of the Hyper-V window. Several additional executable files (DPMIInst.exe, DPMILoad.exe, and RTM.exe) plus a binary overlay file (DPMI16bi.ovl) were also required in the same folder.

Auxiliary files—

Under the main AUTOSAW folder, a subfolder named INIT must be created and several graphic-support files, font files, and a binary definition file must be copied there (FRI 1994). In addition, the folder must contain six AUTOSAW definition files, which are text files that provide information used by the sawing simulator. These files—Autosaw.def, Autoset.def, Autoedge.def, Cantsaw4.can, Edge2.def, and Livesaw4.liv—can be revised using a text editor to change default settings. However, we left them unchanged.

Parameter file—

AUTOSAW requires a parameter file to provide information about the sawmill being simulated, the type of products to be sawn, settings for various parameters used during the sawing simulation, and the lumber grading rules to be used. The file can have any name but must have an extension of either CAN or LIV, depending on whether cant sawing or live sawing is to be simulated. Because we elected to use cant sawing, we created a parameter file named STUDS.CAN. Information from the STUDS.CAN file used for our simulations is summarized in table 30.

Command file—

We ran AUTOSAW in automatic-simulation mode, rather than interactive mode, because of the large number of logs to be sawn. This mode requires a text file with an extension of AUT that provides information to AUTOSAW on the type of sawing to be done and the number and location of the data files for the short logs to be processed. As an example, the format of the AUT file is:

```
STUDS.CAN
4
C:\AUTOSAW\STUDS\Y_DAT\1016-1-1.dat
C:\AUTOSAW\STUDS\Y_DAT\1016-1-2.dat
C:\AUTOSAW\STUDS\Y_DAT\1016-2-1.dat
C:\AUTOSAW\STUDS\Y_DAT\1016-2-2.dat
```

These instructions tell AUTOSAW that cant sawing is to be simulated and the sawing parameters are to be found in STUDS.CAN, which is located in the same folder as the AUT file. Four logs are to be sawn and the DAT files for these logs are found in the C:\AUTOSAW\STUDS\Y_DAT folder.

Operation

To execute a simulation run, the user opens a command window by executing the **cmd.exe** command-line processor, then navigates to the folder where the AUT file is located and launches AUTOSAW by typing the filename (**Autosaw.exe**) at the command line and pressing the Enter key. If the executable file is located in a different folder than the AUT file, the location of the executable file can be specified by prefixing either a relative or absolute path to the executable filename. For instance, if Autosaw.exe is located in the C:\Autosaw folder, typing C:\Autosaw\Autosaw.exe at the command line will launch the simulator. After the simulator has been launched, the user chooses the option to initiate an automated simulation run and enters the name of the AUT file. AUTOSAW reads the file and processes the logs one by one according to the parameters specified in the CAN file.

Output Files

For each log specified in the AUT file, an AUTOSAW simulation produces one file with an extension of CON and another with an extension of OUT. It also produces a single file with the same base name as the AUT file but with an extension of SWN. This file contains a summary of the total volume of lumber produced from each log

Table 30—Summary of sawing instructions used for the AUTOSAW simulations as specified in the STUDS.CAN parameter file; most numerical data except nominal lumber dimensions are specified in millimeters and conversions are shown in parentheses to units of measure that are commonly used in Douglas-fir sawmills

Specification	Description
Log presentation	Small end toward the saw
Headrig saw	Vertical bandsaw
Log position	Centered on the carriage with the log rotated into the same position as initially measured (y-axis pointing vertically upward) except that logs with sweep are rotated instead to the "horns up" orientation.
Sawing method	Half-taper cant sawing (cants are sawn with edges parallel to the center; i.e., the longitudinal axis, of the log)
Headrig sawkerf[a]	3.6 mm (0.142 inch)
Cant breakdown sawkerf[a]	3.6 mm (0.142 inch)
Edger sawkerf[a]	3.8 mm (0.150 inch)
Trim increment	304.8 mm (1 foot)—each piece length is an even multiple of this after trimming
Minimum piece length	1829 mm (6 feet)
Maximum wane permitted	10 mm (0.4 inch) along each edge
Pith diameter	10 mm (0.4 inch)
Cant width (nominal)	4, 6, 8, 10, or 12 inches
Cant width (rough-sawn)[a,b,c]	97, 150, 198, 249, or 300 mm (3.82, 5.91, 7.80, 9.80, or 11.81 inches).
Minimum log small-end diameter for corresponding cant widths	101.6, 152.4, 203.2, 254.0, or 304.8 mm (4, 6, 8, 10, or 12 inches)
Lumber thickness (nominal)	1 or 2 inches
Lumber thickness (rough-sawn)[a,b]	24.6 or 46.5 mm (0.97 or 1.83 inch)
Lumber width (nominal)	4, 6, 8, 10, or 12 inches
Lumber width (rough-sawn)[a,b]	97, 150, 198, 249, or 300 mm (3.82, 5.91, 7.80, 9.80, or 11.81 inches)
Edging methodology	Edge to maximize volume, testing all possible width combinations
Lumber grading rules:	
1-inch boards	Common boards (WWPA 2005)
2 × 4 pieces	Structural light framing (WWPA 2005)
2 × 6, 2 × 8, 2 × 10, 2 × 12 pieces	Joists and planks (WWPA 2005)
Lumber grades:	
1-inch boards	Common No. 1, 2, 3, 4, 5
2 × 4 pieces	Select Structural, No. 1 (construction), No. 2 (standard), No. 3, economy
2 × 6, 2 × 8, 2 × 10, 2 × 12 pieces	Select Structural, No. 1 (construction), No. 2 (standard), No. 3, economy

[a] Median values from eight sawmill studies on second-growth Douglas-fir as recorded in the product-recovery database located at the U.S. Forest Service, Pacific Northwest Research Station, Forestry Sciences Laboratory, 620 SW Main Street, Portland, OR 97205.

[b] These dimensions are for rough-sawn lumber before it shrinks from drying and is reduced by surfacing.

[c] Although cant widths are specified as equal to lumber widths, AUTOSAW expands the cant width to account for the internal saw kerfs that will be needed when the cant is reduced into individual pieces.

in the simulation, measured in cubic meters. Rather than use information from this file, we wrote the program described below to aggregate detailed results from the OUT files into a single Excel file.

CON and OUT files have the same base name as the AUT file, up to the first six characters of the filename stem, plus an index number that begins at 1 for the first DAT file specified in the AUT file and runs up to the number of logs sawn in the simulation. For example, if an AUT file named Cataract.AUT lists 30 short-log DAT files to be sawn, the CON files would be named Catara1.CON, Catara2.CON, ... Catara29.CON, Catara30.CON. The OUT files from the same simulation run would have corresponding names but with an OUT extension. Because the maximum value of the index is 99, no more than 99 DAT files can be specified in an individual AUT file. Multiple AUT files can be used to run all logs for the study.

Each CON (continuation) file is a binary file that stores a record of the sawing simulation for an individual log. The CON file can be loaded into AUTOSAW using its Continue with Old Run option and the results of the simulation can then be visualized or processed further. This is how the images in figure 24 were produced.

Each OUT file is a text file listing each piece of lumber produced in the simulation along with its dimensions and assigned grade. The software discussed below uses these files to compile a spreadsheet with complete results for all of the logs processed in an entire simulation run.

Compiling AUTOSAW Simulation Results

Because an AUTOSAW simulation produces an OUT file for each log sawn, we wrote a program to aggregate the product information for all logs sawn during a simulation run into a single Excel file. This corresponds to step 6 in figure 8. The conversion program was written in the C# programming language and uses Excel automation in the same way as the bucking program described in appendix 2. Following is a brief description of the output-aggregation program:

Executable file (xlFromOutfiles.exe)—
This file can simply be copied into any folder on the user's computer without formal installation; administrative privileges are not required. The user's computer must meet the same requirements as the bucking simulator (app. 2), and the executable file may need to be unblocked before its first use (app. 1).

Supporting files (Template.xls and Template.xlsx)—
These two Excel files must be present in the same folder as the executable file. The XLS file is used as a template to produce an output file if the user's computer has Excel 2002 or 2003 installed, and the XLSX file is used as a template for Excel 2007 or later. The contents of the two template files are identical. Each contains

two worksheets, one named Autosaw Results and the other named WWPA Grades. Data from the AUTOSAW OUT files are written to the first worksheet, with each row corresponding to a single piece of lumber. Formulas in that worksheet then use information from the second worksheet to convert AUTOSAW grades into the corresponding WWPA (2005) grades and to create a report summarizing the lumber produced by the simulation.

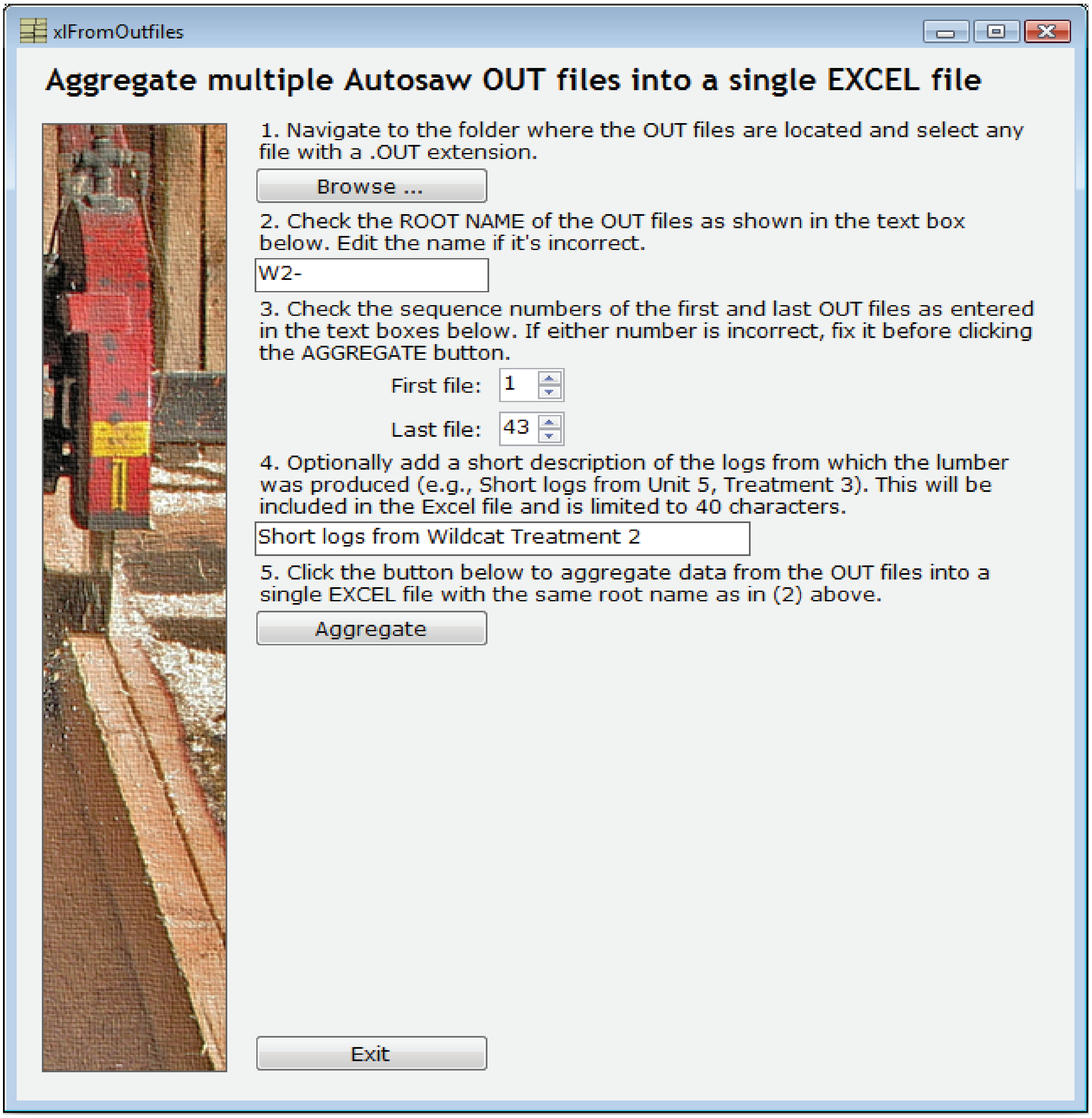
Operation—
The user navigates to the folder where the executable file has been placed and double-clicks the filename to launch the program. The user interface for this program is shown in figure 25. In step 1 the user browses to a folder containing output files from an AUTOSAW simulation and selects any file with an OUT extension. The program then infers the root name of the OUT files (step 2); in figure 25 this is W2-, implying that the OUT files are for the lightly thinned treatment at the Wildcat site and that individual OUT files are named W2-1.out, W2-2.out, and so on. The root name can never be longer than six characters, because AUTOSAW reserves two characters for the file index values and the names of OUT files cannot exceed eight characters under MS-DOS® naming rules. In step 3, the program determines the number of OUT files with that root name in the folder; the file index values in figure 25 run from 1 through 43. The user can enter a short description of the logs from which the lumber was produced (step 4) and then click the Aggregate button (step 5) to create the Excel file.

Input files—
This is a set of OUT files from an AUTOSAW simulation. These files must be located in a single folder and they must all have the same root name.

Output files—
Two files are produced: _LogList.txt and either Root.xlsx or Root.xls, where Root is replaced by the root name of the set of OUT files described above. The Excel file created as the primary output has the extension XLSX or XLS depending on the version installed on the user's computer. For the illustration in figure 25 the output filename would be W2-.xlsx or W2-.xls.

The _LogList.txt file is a simple text file that provides a one-to-one mapping of OUT files to the corresponding short-log identifiers, such as the following example for two of the logs being processed:

Filename	Log ID
W2-1.out	W2-1008-1-1
W2-2.out	W2-1008-1-2



Aggregate multiple Autosaw OUT files into a single EXCEL file

1. Navigate to the folder where the OUT files are located and select any file with a .OUT extension.

2. Check the ROOT NAME of the OUT files as shown in the text box below. Edit the name if it's incorrect.

W2-

3. Check the sequence numbers of the first and last OUT files as entered in the text boxes below. If either number is incorrect, fix it before clicking the AGGREGATE button.

First file: 1

Last file: 43

4. Optionally add a short description of the logs from which the lumber was produced (e.g., Short logs from Unit 5, Treatment 3). This will be included in the Excel file and is limited to 40 characters.

Short logs from Wildcat Treatment 2

5. Click the button below to aggregate data from the OUT files into a single EXCEL file with the same root name as in (2) above.

Figure 25—The user's interface for the xlFromOutfiles program, which aggregates multiple output files from AUTOSAW into a single Microsoft Excel file.

The Excel file produced by the program contains a complete listing of all lumber produced by the AUTOSAW simulation as well as a summary of the number of pieces and volume of lumber in each piece size, and a separate summary of the volume produced by lumber grade.

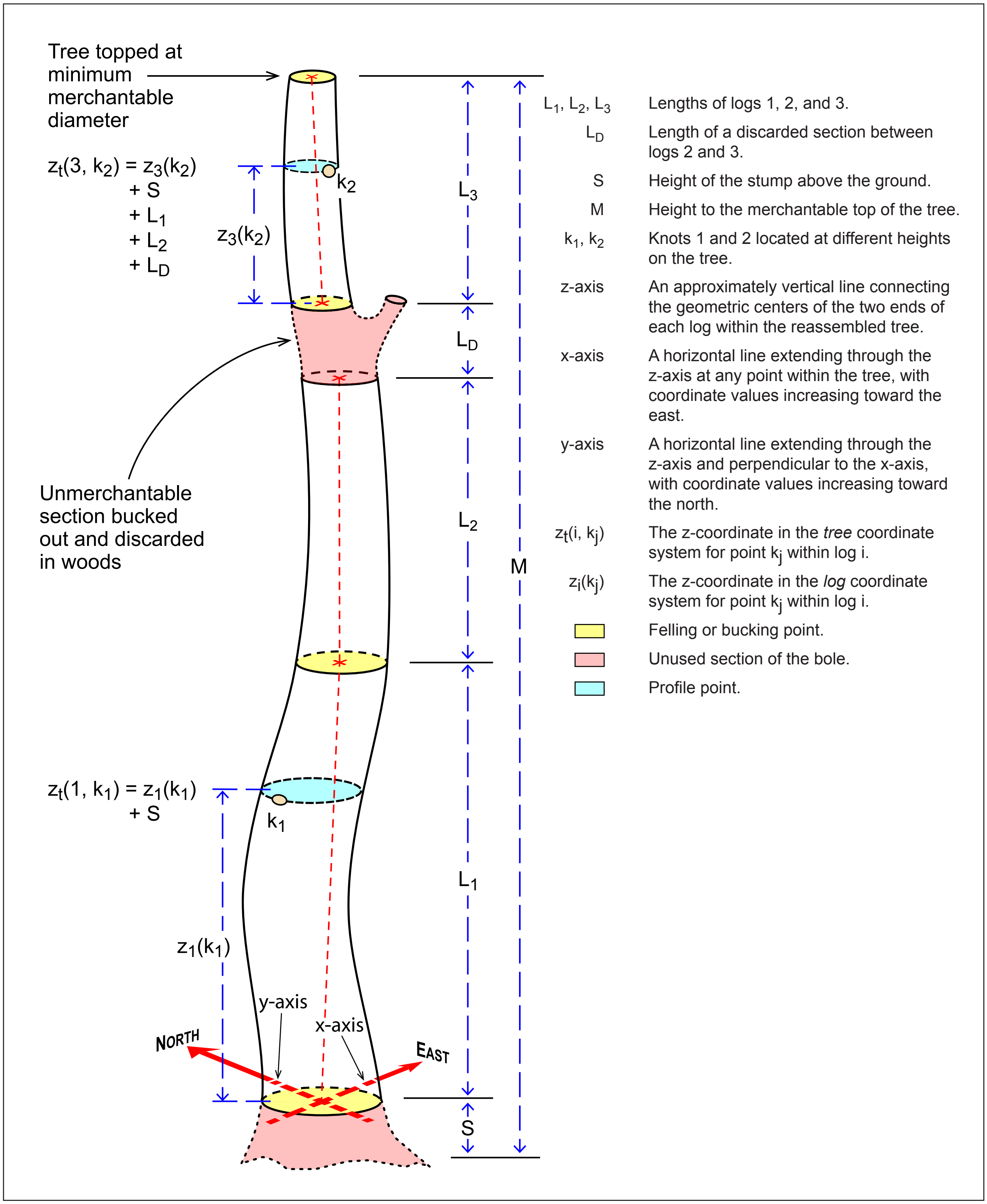
Appendix 4: Three-Dimensional Data for Standing Trees

This appendix describes the procedures and assumptions used to convert data from long-log Microsoft Excel worksheets into a three-dimensional dataset in a single Excel worksheet comprising information on profile points and branch locations for standing trees. We developed a computer program in the C# programming language (xlLogToTree3D.exe) to reassemble long logs into the standing trees from which they came and then derive three-dimensional coordinates for profile points and branch locations (surface knots). We used long-log (woods-length) data rather than short (mill-length) log data because they are more complete. The long-log worksheets include information on sections of logs that were trimmed off and discarded during the simulated bucking process (app. 2), whereas the short-log worksheets by definition omit this information. By combining data for all long logs from each sample tree and accounting for short sections of tree stems that were bucked out and left in the woods, we were able to put together three-dimensional data on profile points and branch locations (surface knots) for individual trees up to the height at which each was topped (fig. 26). We refer to this as merchantable height of the tree, although in some instances it was beyond the limit of merchantability, defined for this study as the height at which the stem diameter drops to four inches. Occasionally the stem diameter at the merchantable height determined in this way was larger than the minimum merchantable diameter because breakage or defects located near the top of the tree prevented the logger from including the top log all the way to the 4-inch limit.

Constructing a virtual tree from the individual long logs requires knowledge about how the logs originally fit together within the tree. From the methodology used to record data for each long log, we know the location of each log within the tree stem and, for most logs, the azimuth toward which the longitudinal axis of the log faced in the standing tree. At each measured profile point we can also calculate coordinates for the center of the log and for any point on the surface of the log (app. 3). Because the measurement methodology was designed to provide this information in log coordinates for the sawing simulator, a different procedure is required to convert the log-based coordinates into tree coordinates.

Deriving z-Coordinates for Points Within the Standing Tree

As shown in figure 26, the known locations of the logs within the standing tree can be used in a relatively simple way to derive a tree-based z-coordinate for each profile point. This z-coordinate measures the height above the ground of any point within the measured tree stem. Given that each log-based z-coordinate was measured as a distance from the large end of each log, the corresponding tree-based z-coordinate can be calculated as follows:



L_1, L_2, L_3	Lengths of logs 1, 2, and 3.
L_D	Length of a discarded section between logs 2 and 3.
S	Height of the stump above the ground.
M	Height to the merchantable top of the tree.
k_1, k_2	Knots 1 and 2 located at different heights on the tree.
z-axis	An approximately vertical line connecting the geometric centers of the two ends of each log within the reassembled tree.
x-axis	A horizontal line extending through the z-axis at any point within the tree, with coordinate values increasing toward the east.
y-axis	A horizontal line extending through the z-axis and perpendicular to the x-axis, with coordinate values increasing toward the north.
$z_t(i, k_j)$	The z-coordinate in the *tree* coordinate system for point k_j within log i.
$z_i(k_j)$	The z-coordinate in the *log* coordinate system for point k_j within log i.
🟨	Felling or bucking point.
🟥	Unused section of the bole.
🟦	Profile point.

Figure 26—The methodology for determining coordinates of profile points and branch locations in a standing tree from long-log data; note that—unlike z-coordinates—the x- and y-coordinates are independent of the height of the profile point in the tree but must be determined relative to axes that are constant for the entire tree stem.

$$z_t\,(i,P)=z_i(P)+\sum_{j=0}^{i-1}L_j$$

where:

z_t (i, P) = the tree-based z-coordinate for any point P measured within log i,

z_i (P) = the log-based z-coordinate for point P measured within log i,

L_j = stump height, S, when $j = 0$, otherwise the total length of log j.

We did not measure stump height, so we assume it is 1 foot for all sample trees in the STUDS project. Based on field observations this is a reasonable average, but of course it does not capture the actual variation inherent when trees are felled on varying slopes.

In addition to the calculation in the above equation, the tree-based z-coordinate must be adjusted for any unmerchantable sections of the tree stem that were bucked out below log i and discarded. Figure 26 shows one such section between logs 2 and 3. Of the 66 sample trees in this study, the logger discarded a portion of the merchantable part of the stem for only four trees, and one broken log was rebucked at the landing to discard the broken section, resulting in the second and third merchantable logs from what had been a two-log tree. Data for the discarded sections were recorded as summarized in this tabulation:

Discarded sections

Tree	Location	Length (feet)	Description
C2-1035	Between log 1 and log 2	14.0	Broken, crooked piece
C2-1570	Between log 2 and log 3	12.0	Lengthwise split through the stem
Y2-1659	Between log 2 and log 3	3.8	Broken log rebucked at the landing
Y3-2002	Between log 2 and log 3	4.0	Stem crushed at this point
Y3-2532	Between log 2 and log 3	3.0	Short broken piece

We did not measure knots or other surface defects within the discarded sections, so deriving profile or branch data for those sections was not possible. Measurements for each discarded section were limited to the length of each discarded piece and the diameters at both ends of the piece.

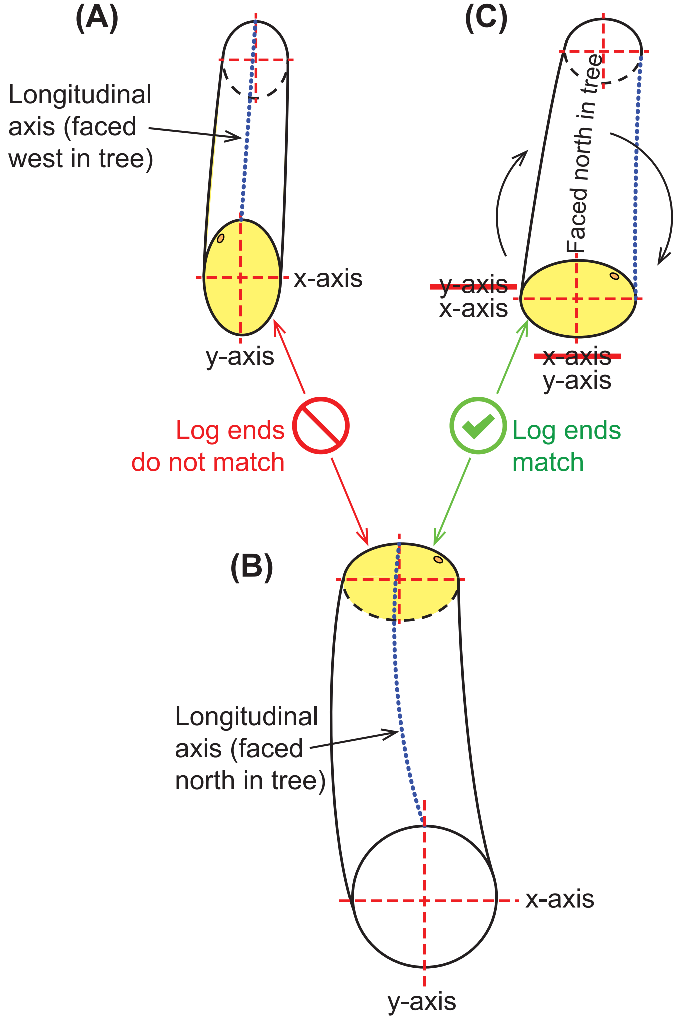
The methodology described above and shown in figure 26 for converting log-based z-coordinates to tree-based z-coordinates involves two approximations. First, z-coordinates for each log were measured along the longitudinal axis of the log rather than along the z-axis—the longitudinal axis is a projection of the center of the log onto the surface of the log along its length (fig. 7), whereas the z-axis is a straight line joining the geometric centers of the two ends of the log. For a log with sweep or crook, this means that the measured z-coordinate is slightly longer than the corresponding distance along the z-axis. For this study, we ignore this error because for our sample logs it was always less than 0.1 foot—the limit of precision for our length measurements (app. 2). If larger errors were encountered, a correction would be necessary.

A further approximation in the above methodology is that the z-axes of individual logs within a tree may not all be vertical. This would cause slight differences between the assumed vertical-length measurements shown in figure 26 and the actual distances along the z-axes of the logs. For most Douglas-fir trees, any such error is likely to be very small; also, because our measurement procedures did not capture the information that would be necessary to adjust for this type of error, we had no other option but to ignore it.

Deriving x- and y-Coordinates for Points Within the Standing Tree

The methodology used to derive tree-stem x- and y-coordinates for profile points and branch locations (surface knots) is more complex than the procedure outlined above for deriving z-coordinates, and is also potentially subject to somewhat larger errors. The procedure for calculating x- and y-coordinates for logs as described in appendix 3 uses an arbitrary log-based coordinate system that is appropriate for the sawing simulator but is not guaranteed to correctly orient logs from a particular tree relative to one another. Reconstructing tree stems from their constituent logs requires the establishment of a single, tree-based coordinate system that can be used to calculate x- and y-coordinates for all profile points and branch locations in all logs cut from the tree. The reason for this is illustrated in figure 27. When the upper log identified as log 2 in figure 27 was measured in its 0° orientation following the procedure outlined in figure 7, its longitudinal axis lay along a surface that had faced toward the west (azimuth 270°) in the standing tree. The longitudinal axis for the butt log (identified as log 1 in fig. 27), however, lay along a surface that had faced toward the north (azimuth 0°) in the standing tree. If the two logs are to be virtually reassembled as they originally fit within the tree, one of them must be “rolled” by 90° (the acute angle between azimuths of 270° and 0°) and its coordinate system reoriented to match that of the other log. This is accomplished by rolling the upper log until the surface that in the standing tree had faced toward the north is at the top of the log. Then the x- and y-axes of log 2 are rotated to match those of log 1. Once this has been done, the coordinates of all objects within log 2 can be recalculated using the tree-stem coordinate system and they will be consistent with the coordinates of objects within log 1.

Rather than base tree-stem coordinates on the axes established arbitrarily for one log from each tree, we decided instead to establish a coordinate system that is identical for all sample trees measured for the entire study. This coordinate system defines the x-axis as running east and west, with a positive value for x toward the east; and the y-axis as running north and south, with a positive value of y toward the north. The two axes intersect at every point along the z-axis of the tree, where x = y = 0. Thus, in figure 26 the x-axis shown at the top of the stump is a west-east



x-axis	A horizontal line extending through the pith and to the perimeter at each end of the log and at any profile point in the log.
y-axis	A vertical line perpendicular to the x-axis extending through the pith at each end of the log and at any profile point in the log.
Longitudinal axis	A line along the length of a log parallel to the path followed by the pith at the center of the log; a straight line if the log is straight or a curved line if the log has sweep or crook.

Figure 27—Reconstructing a tree stem from its long logs after simulated bucking requires that x- and y-axes for the logs align correctly, as in this example: (A) the longitudinal axis used as a reference to establish the x- and y-axes for log 2 faced west in the standing tree; whereas (B) the longitudinal axis for log 1 faced north, causing data for the two logs to be based on different coordinate systems; and requiring (C) the virtual "rolling" of one log as needed until the two coordinate systems matched, then recalculating the x- and y-coordinates of objects within the rolled log.

line and the y-axis is a south-north line. The z-axis is assumed to extend vertically upward from the center of the stump, which as noted earlier, is assumed to be a foot above ground level. In three-dimensional coordinates, denoted {x, y, z}, the center of the stump (or equivalently the center of the large end of the butt log) is always at point {0, 0, 304.8}, with coordinates expressed in millimeters. Similarly, if the butt log has a length of 11,277.6 mm (37 feet), the center of the small end of the log would have coordinates {0, 0, 11582.4}. For this exercise all coordinate values are expressed in millimeters even though the original measurements were in feet and inches.

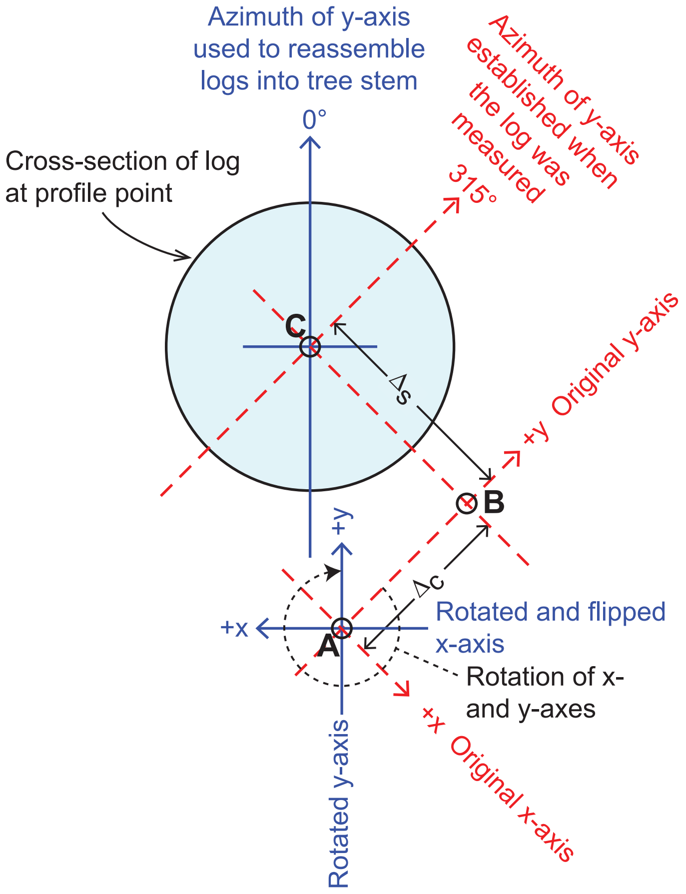
Mirror images—

The x- and y-axes defined as described above for the tree stem are mirror images of the axes that were established when measuring individual logs. This has implications for the way the log axes must be rotated to ensure an equivalent tree-stem coordinate system, and also affects numerical values along the x-axis. To visualize the effect on x-coordinates, consider log 1 in figure 27. The y-axis of the log points toward the direction that the top surface of the log faced in the standing tree; this is shown in the image as north. Because of the way the log-coordinate system was established, the positive values of the x-axis increase toward the right, which in the standing tree was the surface of the log that faced west. In tree-stem coordinates the y-axis also points toward north, but positive values of the x-axis increase toward the east as shown in figure 26. As a result, for log 1 in figure 27, surface defects on the side of the log that faced west in the standing tree will have positive log x-coordinates but negative tree-stem x-coordinates.

Rotating axes and calculating center coordinates—

The initial step in computing x-and y-coordinates for objects at any log profile point is to derive the coordinates at the center of the stem corresponding to the profile point. The procedure we followed for doing this is illustrated in figure 28 and described below.

1. In figure 28, point C is at the center of the log and corresponds to a profile point for which coordinates of surface defects or other features are needed. Point C is the base from which these coordinates must be calculated for the profile point. The azimuth of the y-axis established when the log was measured was 315°. The log in the example has both a sweep offset of Δs parallel to the x-axis at point C and a crook offset of Δc parallel to the y-axis at point C.
2. The azimuth of the original y-axis as shown in figure 28 is the direction toward which the top surface of the log in its initial measurement orientation would have faced when the log was in the standing tree. For tree-stem coordinates, the y-axis should point north, corresponding to an azimuth of 0°, so the y-axis in the figure must be rotated from 315° to 0°. Because the x- and y- axes are orthogonal by definition, both must be rotated equally.
3. If it seems odd that the original y-axis with an azimuth of 315° is shown to the right of the rotated y-axis at 0°, remember that our point of reference for log coordinates (shown in the image) is from the large end of the log looking toward the small end of the log and thus toward the top of the tree. But for stem coordinates, the point of reference is the tree as it stood on the stump (fig. 26). Therefore the x- and y-axes shown in figure 28 represent



z-axis	An imaginary straight line between the geometric centers of the two ends of a log.
x-axis	In original log coordinates, a horizontal line extending through the geometric center of the log at each end; in rotated coordinates, a horizontal line extending through the geometric center of the tree stem at any point and pointing east.
y-axis	In original log coordinates, a vertical line perpendicular to the x-axis and intersecting the geometric center of the log at each end; in rotated coordinates, a horizontal line perpendicular to the x-axis extending through the geometric center of the tree stem at any point and pointing north.
C	A point at the center of a log for which the locations of surface defects are to be calculated in tree-stem coordinates.
A	Location of the z-axis, offset from C by sweep and crook. In this figure the axis is a single point because it is perpendicular to the plane of the page.
B	A point on the original y-axis where it intersects a line drawn through point C and parallel to the original x-axis.
Δ_S	The sweep offset (B to C) in original coordinates. In this example the sweep offset is parallel to the original x-axis and in the negative x direction (leftward).
Δ_C	The crook offset (A to B) in original coordinates. In this example the crook offset is parallel to the original y-axis and in the positive y direction (upward).

Figure 28—Cross sectional view of a log at an arbitrary stem profile point after simulated bucking, showing the procedure used to rotate the x- and y-axes and flip the x-axis, thereby converting the log coordinate system into a tree-stem coordinate system with the y-axis pointing north and the x-axis pointing east.

mirror images of the axes as they would be viewed from the perspective of the standing tree.

4. The point around which the x- and y-axes rotate is the z-axis. This point lies outside of the log cross section because of sweep and crook at this profile point. For an example of such a situation, refer to figure 21, where the z-axis is located outside the log at point D and is associated with the profile point centered on the bucking point.
5. Rotation of the x- and y-axes is shown in figure 28, where the original axes are drawn in red and the rotated axes in blue.
6. Because of the difference in perspective between log coordinates and tree-stem coordinates, the x-axis must be "flipped" from west to east after the

rotation described in steps 2 to 5 has been carried out. This is necessary because positive x-coordinates increase toward the west in the log coordinate system but increase toward the east in the stem coordinate system (fig. 26). The difference is a result of the mirror-image relationship between log coordinates and stem coordinates.

7. From the geometry shown in figure 28, the x- and y-coordinates at point C, in tree-stem coordinates, can be calculated as shown below while simultaneously rotating the x- and y-axes about the z-axis and flipping the x-axis. The calculations differ for the two types of offsets (left/right or up/down) because they have different geometric relations.

$$x_C = \sum_{i=0}^{n} s_{1i} \cdot s_{2i} \cdot \Delta_i \cdot f_{xi}(\theta)$$

$$y_C = \sum_{i=0}^{n} s_{2i} \cdot \Delta_i \cdot f_{yi}(\theta)$$

where:

x_C = the x-coordinate at the center of the log profile (point C in fig. 28),

y_C = the y-coordinate at the center of the log profile,

n = the number of sweep and crook offsets measured at the current profile point (n = 2 in fig. 28, which shows one sweep offset and one crook offset),

$s_{1i} = -1$ if the offset direction of Δ_i is left or right (for example Δ_s in fig. 28), or +1 if the offset direction is up or down (for example, Δ_c in fig. 28),

$s_{2i} = -1$ if the offset direction of Δ_i is left or down, or +1 if the direction is right or up,

Δ_i = the sweep or crook offset at point i as determined when the log was measured,

$f_{xi}(\theta) = \cos(\theta)$ if the offset direction of Δ_i is left or right, or $\sin(\theta)$ if the offset direction is up or down,

$f_{yi}(\theta) = \sin(\theta)$ if the offset direction of Δ_i is left or right, or $\cos(\theta)$ if the offset direction is up or down,

θ = the azimuth of the original y-axis before the rotation (315° in fig. 28).

In the equation for x, the –1 value of s_{1i} for left and right offsets flips the x-axis from west to east as described in point 6 above.

To illustrate the procedure outlined above, consider the situation illustrated in figure 28. At the profile point shown, adjustments must be made for one crook offset and one sweep offset. The extent of each offset at the profile point is calculated from the original measurement data using the procedure described in appendix 2. Offset calculations at any profile point use the same methodology for both sweep and crook except that sweep extends over the entire length of the log whereas crook has a specified beginning and end within the log. Suppose that for the situation in figure 28 the two offsets have been determined to be the following:

- Crook offset: up 117 mm, or about 4.6 inches (the distance from point A to point B)
- Sweep offset: left 148 mm, or about 5.8 inches (the distance from point B to point C)

The "up" and "left" qualifiers are expressed in terms of the original x- and y-axes that were established when the log was measured. Using the equations for x_C and y_C as described in step 7 above, the tree-stem coordinates at point C are calculated as shown below, where $i = 1$ for the crook offset and $i = 2$ for the sweep offset. These specific values for i are arbitrary; the order in which the offsets are calculated makes no difference to the outcome. Variables in the equations are established as: $s_{11} = +1$ because offset 1 (crook) has an up or down direction; $s_{21} = +1$ because offset 1 (crook) is up; $\Delta_1 = 117$; $f_{xi}(\theta) = \sin(\theta)$ because offset 1 (crook) has an up or down direction; $f_{y1}(\theta) = \cos(\theta)$ because offset 1 (crook) has an up or down direction; $s_{12} = -1$ because offset 2 (sweep) has a left or right direction; $s_{22} = -1$ because offset 2 (sweep) is to the left; $\Delta_2 = 148$; $f_{x2}(\theta) = \cos(\theta)$ because offset 2 (sweep) has a left or right direction; $f_{y2}(\theta) = \sin(\theta)$ because offset 2 (sweep) has a left or right direction.

Then calculate the coordinates of point C as follows:

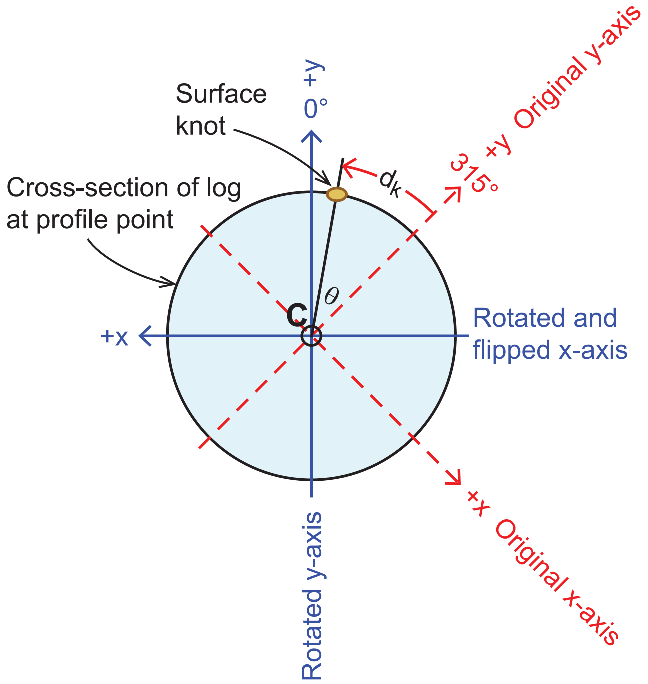
$$x = [s_{11} \cdot s_{21} \cdot \Delta_1 \cdot f_{x1}(\theta)] + [s_{12} \cdot s_{22} \cdot \Delta_2 \cdot f_{x2}(\theta)]$$
$$= [+1 \cdot +1 \cdot 117 \cdot \sin(315°)] + [-1 \cdot -1 \cdot 148 \cdot \cos(315°)] = -82.7 + 104.7 = 22.0 \text{ mm}$$

$$y = [s_{21} \cdot \Delta_1 \cdot f_{y1}(\theta)] + [s_{22} \cdot \Delta_2 \cdot f_{y2}(\theta)]$$
$$= [+1 \cdot 117 \cdot \cos(315°)] + [-1 \cdot 148 \cdot \sin(315°)] = +82.7 + 104.7 = 187.4 \text{ mm}$$

Calculating coordinates of surface defects—

Below is a description of the procedure for calculating the coordinates of surface defects on the reassembled tree stem, as illustrated in figure 29.

1. Locations of surface defects have been measured as offsets from the longitudinal axis of the log, measured along the curve of the log surface (fig. 7). Figure 29 shows a surface knot on the profile point from figure 28. The location of the surface knot has been recorded as left from the longitudinal



x-axis	In original log coordinates, a horizontal line extending through the geometric center of the log at each end; in rotated coordinates, a horizontal line extending through the geometric center of the tree stem at any point and pointing east.
y-axis	In original log coordinates, a vertical line perpendicular to the x-axis and intersecting the geometric center of the log at each end; in rotated coordinates, a horizontal line perpendicular to the x-axis extending through the geometric center of the tree stem at any point and pointing north.
C	A point at the center of a log for which the locations of surface defects are to be calculated in tree-stem coordinates.
d_k	Offset to a surface knot as measured from the original y-axis of the log.
θ	The angle corresponding to offset d_k.

Figure 29—Cross-sectional view of a log showing the procedure for calculating the tree-stem coordinates of a surface knot when the offset to the knot from the original y-axis of the log is known.

axis a distance of d_k. The first step in the calculation procedure is to determine the angle between the longitudinal axis of the log (the original y-axis) and a line drawn from the center of the log through the center of the surface knot. In figure 29, this angle is denoted θ. It can be calculated as:

$$\theta = d_k \cdot 360 / (\pi \cdot D_C)$$

where:

θ = the angle in degrees between the original y-axis and a line drawn from the center of the log at point C through the center of the surface knot,

d_k = the offset distance from the original y-axis to the center of the surface knot as measured along the curve of the log surface (units of measure must be the same as those for D_C below),

360 = the number of degrees in a full circle,

π = the ratio of the circumference of a circle to its diameter,

D_C = the diameter of the log at profile point C (units of measure must be the same as those for d_k above).

2. Calculate α_k, the azimuth that the surface knot faced in the standing tree, using α_y to denote the azimuth of the original y-axis (315° in fig. 29): If the surface knot is to the left of the original y-axis of the log, $\alpha_k = \alpha_y + \theta$; if it is to the right of the original y-axis, $\alpha_k = \alpha_y - \theta$. If the result is larger than 360, subtract 360 from α_k; if the result is less than 0, add 360 to α_k.
3. Calculate the tree-stem coordinates of the surface knot as:

$$x_k = x_C + \left(\frac{D_C}{2}\right)\cdot \mathrm{Sin}(\alpha_k)$$

$$y_k = y_C + \left(\frac{D_C}{2}\right)\cdot \mathrm{Cos}(\alpha_k)$$

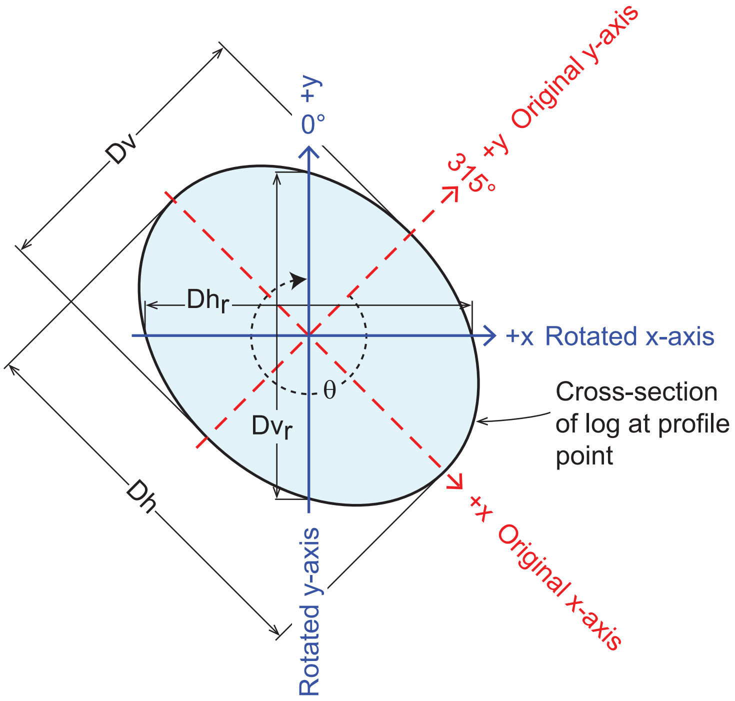
where:

x_k = the x-coordinate at the center of the surface knot,
y_k = the y-coordinate at the center of the surface knot,
x_C = the x-coordinate of the center of the log profile (point C in fig. 29),
y_C = the y-coordinate of the center of the log profile,
D_C = the diameter of the log at profile point C,
α_k = the azimuth faced by the surface defect in the standing tree as derived in step 2 above.

Rotating elliptical diameters—

The final adjustment needed to complete the conversion of log-based data into the equivalent tree-stem data is to rotate the elliptical diameters at the two ends of each log and adjust the diameter measurements along the rotated x- and y-axes. In the Siuslaw Thinning and Underplanting for Diversity Study (STUDS) project, we took both horizontal and vertical diameter measurements only at the two ends of each log. Diameters at all other profile points were recorded from only a single horizontal-diameter measurement. For the vertical measurements, therefore, we were forced to assume that the log cross section is circular. However, the dual measurements at each end of the log permitted us to use elliptical geometries for those two profile points in each log. This was consistent with AUTOSAW, which assumes that log cross sections are elliptical.

Figure 30 illustrates the diameter corrections required when the x- and y-axes are rotated with respect to a log with an elliptical cross section. As before, we rotate the axes from their original positions when the log was measured into a new position that has the y-axis oriented toward north. The figure shows the original y-axis being rotated through an angle θ, which is equal to the azimuth of the original y-axis. The original azimuth of 315° is shown to the right of north because of the mirror-image effect discussed earlier. The x- axis is of course rotated through the angle θ as well; however, the x-axis does not need to be flipped because we are not calculating coordinates. Diameter measurements are absolute values and are invariant regardless of how the log profile is positioned along the x-axis.



x-axis	In original log coordinates, a horizontal line extending through the geometric center of the log at each end; in rotated coordinates, a horizontal line extending through the geometric center of the tree stem at any point and pointing east.
y-axis	In original log coordinates, a vertical line perpendicular to the x-axis and intersecting the geometric center of the log at each end; in rotated coordinates, a horizontal line perpendicular to the x-axis extending through the geometric center of the tree stem at any point and pointing north.
θ	The angle through which the axes of the log must be rotated in order to convert log coordinates into tree-stem coordinates.
Dv	Vertical diameter of an elliptical log before the axes have been rotated.
Dv_r	Vertical diameter of an elliptical log after the axes have been rotated.
Dh	Horizontal diameter of an elliptical log before the axes have been rotated.
Dh_r	Horizontal diameter of an elliptical log after the axes have been rotated.

Figure 30—Geometry of an elliptical profile point after simulated bucking, showing the horizontal and vertical diameter measurements and the equivalent measurements after the axes have been rotated.

The original diameter measurements shown in figure 30 are Dh (the horizontal measurement) and Dv, (the vertical measurement). These are assumed to represent the lengths of the major and minor axes of the ellipse; in figure 30, Dh is the length of the major axis and Dv is the length of the minor axis. After the axes have been rotated, the diameter measurements along the rotated axes are Dh_r (the rotated horizontal measurement) and Dv_r (the rotated vertical measurement). These quantities can be calculated using the following equations derived from the standard formula for the rotation of an ellipse:

$$Dh_r = \frac{Dh \cdot Dv}{2} \cdot \sqrt{\left[\frac{Dv}{2} \cdot \cos(\theta_1)\right]^2 + \left[\frac{Dh}{2} \cdot \sin(\theta_1)\right]^2}\ )$$

$$Dv_r = \frac{Dh \cdot Dv}{2} \cdot \sqrt{\left[\frac{Dv}{2} \cdot \cos(\theta_2)\right]^2 + \left[\frac{Dh}{2} \cdot \sin(\theta_2)\right]^2}\ )$$

where:

Dh_r = the rotated horizontal diameter measurement,

Dv_r = the rotated vertical diameter measurement,

Dh = the original horizontal diameter measurement,

Dv = the original vertical diameter measurement,

θ_1 = the azimuth of the original y-axis established when the log was measured (in figure 30, $\theta_1 = 315°$),

$\theta_2 = \theta_1 + 90°$; if $\theta_2 > 360°$, $\theta_2 = θ1 – 270°$ (in fig. 30, $\theta_2 = 45°$).

Potential errors—
As noted before, the methodology for calculating tree-stem x- and y-coordinates is potentially subject to somewhat larger errors than the methodology for calculating tree-stem z-coordinates. The reason for this is demonstrated in figure 26. The potential for error stems from the fact that individual logs may not be perfectly vertical within the tree stem, resulting in an {x, y} coordinate at the top of a log that is not located directly above the {x, y} coordinate at the bottom of the log. This potential may be especially great for discarded sections, which are frequently crooked or irregularly shaped (fig. 26). Because our measurement methodology was not designed to provide information that can be used to compensate for this type of error, the calculated x- and y-coordinates for the stem above a log or discarded section with a nonvertical z-axis were offset from the true coordinates by an unknown amount. Because the quantity or direction of any such shifts cannot be estimated, we had no choice but to ignore them. Any study that relies on data gathered from individual logs rather than from the standing tree stem will include the possibility of this type of error. Stem-length or whole-tree harvesting could potentially be used but both would require a measurement apparatus designed to provide a fixed reference for the z-axis of the stem.

Depth data for surface defects—
Some surface defects are exposed as gouges or gashes that cut into the stem of the tree. Our data forms did not provide for these defects because AUTOSAW does not use this kind of data and because they are uncommon in second-growth Douglas-fir. However, wherever we found an open wound in the side of a log, we recorded its depth on the data form as a note. Recognizing its potential value for future stem analyses, we converted the information from these notes into data in a Depth column within the surface-defect section of the output files produced by the three-dimensional software described below. Only four instances of this type of information were recorded, as shown in the following tabulation:

Long log	Distance from large end (feet)	Short log	Distance from large end (feet)	Description
C3-2019-1	16.0	C3-2019-1-2	3.5	Gash from forked top 5 inches deep
W2-1247-1	22.2	W2-1247-1-2	5.8	Rotten scar 3 inches deep
W2-1285-2	1.9	W2-1285-2-1	1.9	Forked top scar 1.5 inches deep
Y2-1588-3	12.3	Y2-1588-3-1	12.3	Scar from forked top 2 inches deep

Software Description for Mapping Profile Points and Surface Defects

Developing three-dimensional coordinates for profile points and stem defects (mostly indicating branch locations) is difficult to execute by hand but reasonably straightforward to implement in a computer program. To reassemble individual logs into the standing trees from which they came and then calculate the three-dimensional coordinates, we developed a computer program in the C# programming language that uses Excel automation in the same way as the bucking simulator described in appendix 2. The program uses the methodology described in this appendix. Following is a brief description of the software:

Executable file (xlLogToTree3D.exe)—
This file can be copied into any folder on the user's computer without formal installation; administrative privileges are not required. The user's computer must meet the same requirements as the bucking simulator (app. 2), and the executable file may need to be unblocked before its first use. Appendix 1 provides instructions on unblocking the executable file.

Supporting files—
The LogDataFmt.xml file must be present in the same folder as the executable file. It is identical to the LogDataFmt.xml file that is used with the bucking simulator.

The Template3D.xls and Template3D.xlsx Excel files must be present in the same folder as the executable file. The XLS file is used as a template to produce an output file if the user's computer has Excel 2002 or 2003 installed, and the XLSX file is used as a template for Excel 2007 or later. The contents of the two template files are identical. Each contains two worksheets, one named ProfileData and the other named DefectTypes. Three-dimensional data are written to the first worksheet, with each row corresponding to a measurement point within the tree stem at a specified distance above the ground. The second worksheet contains a listing of the defect codes and corresponding descriptions for all surface defects to be incorporated into the three-dimensional dataset.

Operation—
The user navigates to the folder where the executable file has been placed and double-clicks the filename to launch the program. The user interface for this program is shown in figure 31. When the window opens, the user clicks the Browse button to locate a file of log-data worksheets to be processed. When the file is opened, a list of worksheets appears in the drop-down box below the Browse button. Information about the file is recorded in the large text box near the center of the window; in figure 31, the report indicates that the file contains 48 worksheets with log-profile data.

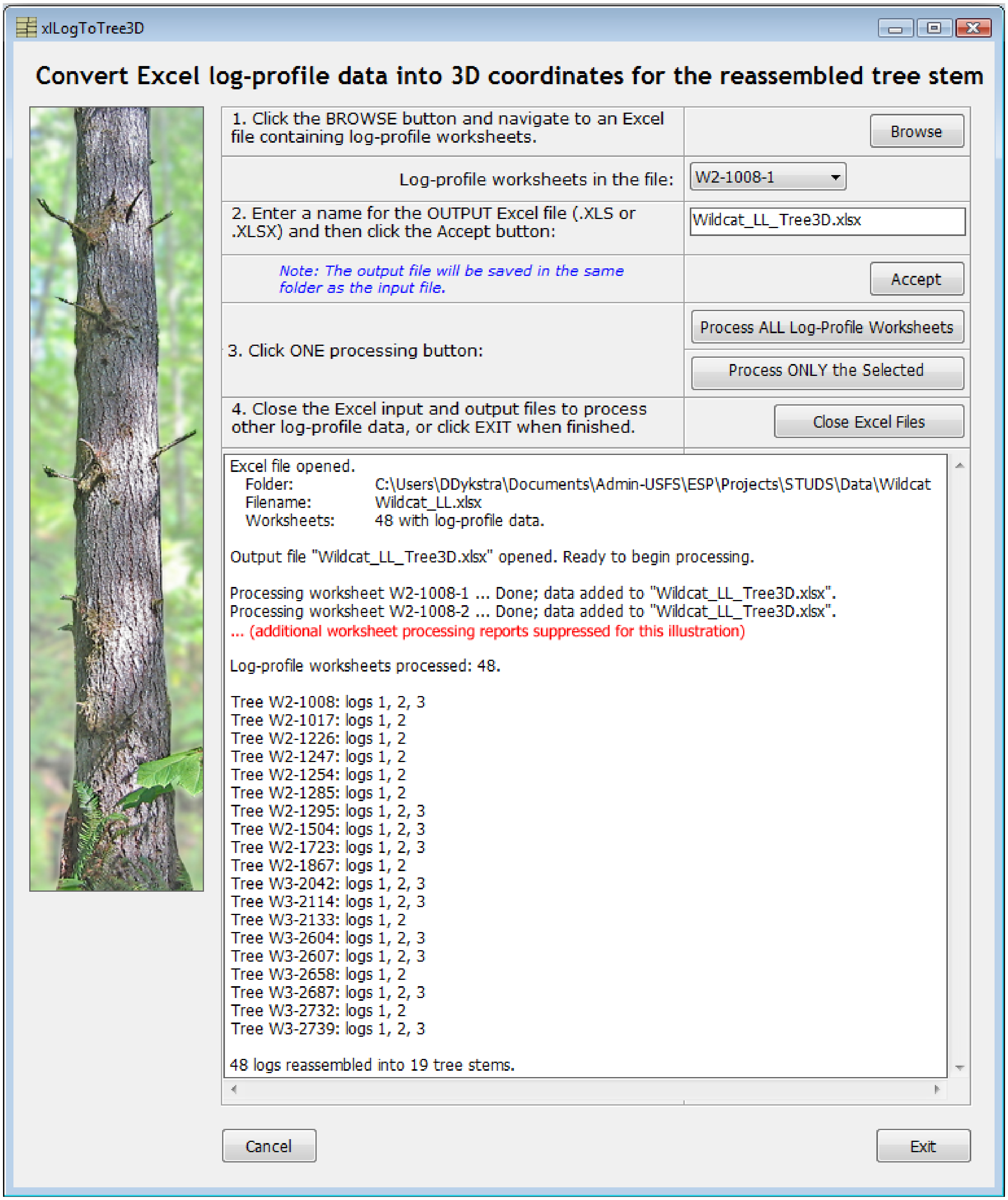
An output filename is entered in the text box (Wildcat_LL_Tree3D.xlsx in fig. 31) and the Accept button is clicked. The output file is created or opened if it already exists and its status is reported in the large text box. The user then clicks one of the two processing buttons (step 3 in fig. 31)—normally, all worksheets are processed but only a single worksheet can be processed if desired. As each worksheet is processed, its status is reported in the large text box; if errors are encountered they will also be described. As the worksheets are being processed, the user can click the Cancel button to halt processing (for instance, if an error is reported) and check the partial output. If processing is allowed to complete, a summary appearing in the large text box reports the number of logs reassembled into each tree stem. For the example in figure 31, the 48 logs were aggregated into 19 tree stems—10 trees with three logs each and the rest with two logs each. After processing has been completed, the user can optionally close the Excel files (step 4 in fig. 31), and then process log-profile data from a different input file; otherwise the user would click the Exit button to close all files and exit the application.

Input file—

This is an Excel spreadsheet file with a filename extension of either XLS (Excel 2002 or 2003) or XLSX (Excel 2007 or later). The file must contain one or more long-log or short-log data worksheets that conform to the format described in LogDataFmt.xml. Each long-log data worksheet must be named in the format Aw-xxxx-y, where A = a single letter representing the site (for the STUDS project, C is Cataract, W is Wildcat, and Y is Yachats); w = a single digit signifying the treatment (for the STUDS project 2 represents the light-thinning treatment T100 and 3 represents the moderate-thinning treatment T60); xxxx = a four-digit tree number; and y = an integer representing the index of the long log (1 = the first long log cut from the stem; 2 = the next long log; and so on). If the data are for short logs, each worksheet must be named in the format Aw-xxxx-y-z, where Aw-xxxx-y is the same as for long logs and z = an integer representing the index of the short log (for example, 1 = the first short log cut from long-log y and 2 = the next short log cut from that same long log). Long-log and short-log data worksheets should not be mixed within a single input file. Stem data aggregated from long logs is likely to be more complete than stem data aggregated from short logs because bucking often results in discarded pieces that will not be accounted for if short-log data are used.

Output—

This is a single Excel file with two worksheets as described above for the Template3D supporting files. The filename is specified by the user and must have an XLS extension if the user's computer has Excel 2002 or 2003 installed; it may have either an XLS or XLSX extension if the user's computer has Excel 2007 or later



Convert Excel log-profile data into 3D coordinates for the reassembled tree stem

1. Click the BROWSE button and navigate to an Excel file containing log-profile worksheets.

Log-profile worksheets in the file: W2-1008-1

2. Enter a name for the OUTPUT Excel file (.XLS or .XLSX) and then click the Accept button: Wildcat_LL_Tree3D.xlsx

Note: The output file will be saved in the same folder as the input file.

3. Click ONE processing button:

4. Close the Excel input and output files to process other log-profile data, or click EXIT when finished.

```
Excel file opened.
   Folder:          C:\Users\DDykstra\Documents\Admin-USFS\ESP\Projects\STUDS\Data\Wildcat
   Filename:        Wildcat_LL.xlsx
   Worksheets:      48 with log-profile data.

Output file "Wildcat_LL_Tree3D.xlsx" opened. Ready to begin processing.

Processing worksheet W2-1008-1 ... Done; data added to "Wildcat_LL_Tree3D.xlsx".
Processing worksheet W2-1008-2 ... Done; data added to "Wildcat_LL_Tree3D.xlsx".
... (additional worksheet processing reports suppressed for this illustration)

Log-profile worksheets processed: 48.

Tree W2-1008: logs 1, 2, 3
Tree W2-1017: logs 1, 2
Tree W2-1226: logs 1, 2
Tree W2-1247: logs 1, 2
Tree W2-1254: logs 1, 2
Tree W2-1285: logs 1, 2
Tree W2-1295: logs 1, 2, 3
Tree W2-1504: logs 1, 2, 3
Tree W2-1723: logs 1, 2, 3
Tree W2-1867: logs 1, 2
Tree W3-2042: logs 1, 2, 3
Tree W3-2114: logs 1, 2, 3
Tree W3-2133: logs 1, 2
Tree W3-2604: logs 1, 2, 3
Tree W3-2607: logs 1, 2, 3
Tree W3-2658: logs 1, 2
Tree W3-2687: logs 1, 2, 3
Tree W3-2732: logs 1, 2
Tree W3-2739: logs 1, 2, 3

48 logs reassembled into 19 tree stems.
```

Figure 31—User interface for xlLogToTree3D.exe, the program created to aggregate log data into the equivalent data for the standing tree after a simulated bucking.

installed. Within the ProfileData worksheet, each row provides data for an individual profile point within the tree stem. Although each data row can provide data for only a single surface defect, multiple data rows can have the same z-coordinate. Data within a specific row include the {x, y, z} coordinate at the center of the stem cross section at the profile point, the diameter of the stem, the azimuth that the surface defect would have faced in the standing tree, the defect-type code from the DefectTypes worksheet, the {x, y} coordinate of the defect (the z-coordinate is the same as that for the center of the stem), the surface dimensions of the defect, the depth of the defect if recorded in a note on the data sheet, and the estimated live and dead lengths within the log if the object is a branch or surface knot. All measurements are in millimeters except the azimuth, which is in degrees. For cross-reference purposes, each row also lists the site, treatment, long-log index, short-log index if the data are for short logs, the data page and data record from the original data-entry sheet, and the tag identifier of the log from which the data row was taken. Any notes attached to the original data row are also transferred to the output file.

Data storage—

All of the three-dimensional data are stored in a single worksheet of the Excel output file described above rather than being organized into separate worksheets by tree. The reason for this is that the worksheet can then be imported into a database as a single data table. Database queries can then be written to access the data by tree, long log, short log, or according to any aggregation or disaggregation criteria that might be desired.

Glossary

1-inch lumber—Lumber sawn into a nominal thickness of 1 inch. In Douglas-fir, widths of 1-inch lumber commonly vary from 4 to 12 inches (nominal measure), although both smaller and larger pieces are sometimes sawn.

Aspect—The compass direction toward which the slope of a land feature faces, often expressed in general terms such as "north-facing" or "west-facing."

Azimuth—A measure of direction on the earth, taken as the compass angle from due north to the object of interest. Thus, due north has an azimuth of 0 degrees; due east, 90 degrees; due south, 180 degrees; and due west, 270 degrees.

Bucking—The act or process of cutting a tree stem into long logs for yarding and transport, or of cutting a long log into short logs for processing in a mill.

Burl—A rounded knotty growth on a tree stem associated with deformed wood grain in the immediate vicinity of the burl.

Butt log—The first log removed from a tree stem immediately above the stump. See also log position.

Cable yarding—A method for transporting woods-length logs from the felling site to a landing (archaic: yard) where the logs can be loaded onto trucks for transport by road to a processing facility. Typically cable yarding is used at sites where the terrain is too steep to permit the use of ground-skidding equipment.

Cant—A thick block of wood sawn from a log that is later sawn further into individual pieces of lumber.

Crook—A curve or bend that extends only partway along the log length. A single log can have more than one crook.

Crown ratio—The ratio of tree-crown length to total tree height.

Dimension lumber—Softwood lumber sawn into nominal thicknesses ranging from 2 to 5 inches, with 2 inches being the most common nominal thickness. In Douglas-fir, dimension lumber typically varies in width from 4 inches to 12 inches (nominal measure), although both smaller and larger pieces are sometimes sawn.

DBH—Diameter of a tree measured at breast height, generally taken as a point 4.5 feet above the average ground level at the base of the tree.

Dead knot—A knot whose fibers are only partially intergrown with the fibers of the surrounding xylem; also known as a loose knot. Dead knots usually have a visible separation between the knot and the surrounding tissue or may appear somewhat decayed at the surface.

Forked top—A defect in a tree stem caused by branching of the stem into two tops. When the tree is felled, the more poorly formed of the two is usually removed and the result is a surface defect similar to a large knot.

Heteroscedasticity—In statistical analysis, a condition in which the variability of a variable is unequal across the range of values of a second variable that predicts it.

Jacket board—A board produced incidentally when sawing a log into lumber. Jacket boards are produced from near the outside of the log (hence the term “jacket”) during the process of converting the round log into a squared cant for subsequent sawing.

Knot—A hard mass of wood where a branch has been severed from the stem of a tree. Knots are the most common defects in lumber manufactured from second-growth Douglas-fir.

Live knot—A knot with fibers that are largely intergrown with the fibers of the surrounding xylem; also known as an ingrown or tight knot.

Log position—The position within the tree stem from which the log was taken. For this study we classified logs as butt, middle, or upper logs. For long logs, the butt log is the first log above the stump and the upper log is the top log removed from the stem. Any logs between these two are classified as middle logs.

Long log—A log created by bucking a tree stem at the felling site into logs that can be yarded to a landing and then transported to a mill in preparation for processing into lumber or another product; also known as a woods-length log.

Lumber recovery—A measure of the quantity of lumber recovered from sawing a specified quantity of logs.

Merchandizing—The process of converting felled tree stems into logs.

Merchantable—A tree or stand that has attained sufficient size, quality, and volume to make it suitable for harvesting and conversion into wood products.

Mill-length log—See the definition for short log.

Middle log—A log extracted from the middle portion of a tree stem. See also log position.

Offset—A distance measured from a reference line to the location of an object such as a knot on the surface of the log.

Overrun—The excess amount of lumber sawn from logs as compared to the amount predicted by a log-scaling rule.

Precommercial thinning—A thinning operation carried out to reduce the density of a stand of trees before the trees have reached sufficient size, quality, or volume to be suitable for conversion into wood products.

Recovery (product, volume, grade, or value)—Any measure of product recovered from a manufacturing process. In lumber, product recovery is usually expressed as the amount of lumber (pieces or volume) recovered per unit (usually volume) of logs used. Recovery may be further specified as the fractions of different grades of lumber recovered per unit of logs used, or as the value of lumber recovered from a specified volume of logs or trees.

Sample log—Any of the logs cut from a sample tree and measured to provide stem and defect data. For this study, only long logs were measured; stem and defect data were then computed for the corresponding short logs by a bucking simulator.

Sample tree—For this study, a tree selected from the population of numbered trees located within 1-acre subplots and marked for removal in the thinning operation.

Short log—A log created by long-log bucking, usually at a mill where the resulting short log will be converted into lumber or other product; also known as a mill-length log. In this study, short logs were produced mathematically by using a computer simulation program to buck long logs.

Sweep—Curvature of a log that extends along its entire length, causing the longitudinal axis of the log to deviate from a straight line. Sweep can be uniform with the maximum sweep occurring at the center of the log, or nonuniform with the maximum sweep occurring at a point nearer one end of the log.

Treatment T30—A treatment in the original 1992 to 1993 commercial thinning on the STUDS project areas that was designed to achieve a residual stocking density of approximately 30 trees per acre.

Treatment T60—A treatment in the original 1992 to 1993 commercial thinning on the STUDS project areas that was designed to achieve a residual stocking density of approximately 60 trees per acre.

Treatment T100—A treatment in the original 1992 to 1993 commercial thinning on the STUDS project areas that was designed to achieve a residual stocking density of approximately 100 trees per acre.

Upper log—A log removed from the upper part of a tree stem. See also log position.

Wane—Missing wood along the edge of a piece of lumber, commonly caused by sawing near the outside of the round log.

Woods-length log—See the definition for long log.

WWPA—Western Wood Products Association, a trade association representing softwood lumber manufacturers in the Western United States. WWPA also serves as the principle authority for defining lumber grading rules for western tree species.

Pacific Northwest Research Station

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