Predicting internal lumber grade from log surface knots: Actual and simulated results

Christine L. Todoroki
Robert A. Monserud*
Dean L. Parry

Abstract

The purpose of this study was threefold: 1) compare actual with simulated lumber yields; 2) examine the effect of measurement errors associated with knot angles and morphology, on lumber grade; and 3) investigate methods for predicting lumber quality within unsawn logs from surface knots. Twenty-eight Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) logs were measured, mapped, sawn, and the lumber dried and graded. A corresponding set of digital log models was developed. Further sets that altered knot azimuth (within measurement error), rake (according to branch distributions), and branch morphology (live or dead) were generated. All log models were processed in the sawing simulator AUTOSAW and the simulated lumber with knot defects was graded to Western Wood Products Association criteria (American Lumber Standards). The simulations showed that lumber grade is sensitive to knot angle, in particular azimuth, and even more so, to morphology. However, other factors not represented in this study have an additional effect on lumber grade. An index, Grade Average, was developed to quantify log quality in terms of lumber grades. In general Grade Average decreased with increasing mean knot diameter. This tendency was stronger for simulated grade yield (r^2 ranging from 0.74 to 0.76) than actual ($r^2 = 0.26$). Grade Average tended to over-predict when there were fewer than 10 surface knots, and to under-predict with smaller diameter logs. The relationship between actual and simulated Grade Average was quite poor (r^2 ranging from 0.10 to 0.11). These results suggest that knowledge of the log surface knots alone is not enough to accurately predict internal lumber grade.

The ability to accurately predict lumber grade contained within unsawn logs is regarded as an important step to improved log sorting, pricing, product differentiation, and enhanced silvicultural planning. Because one of the greatest causes of lumber degrade is due to knots (sawn cross sections of branches), one would expect that the size, distribution, and type of knots on the log surface would provide important information on internal wood quality.

In the past, empirical studies have been performed to study the effect of log features on lumber quality (Cown et al. 1984, Fahey et al. 1991). Models for predicting internal lumber quality from these external features have been developed (e.g., Whiteside 1982, 1990). Now, through development of simulation techniques, the need to perform these studies has been reduced. A notable example is the merging of the crown dynamics research in Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) (Maguire et al. 1994, Roeh and Maguire 1997) with the stand growth simulator ORGANON (Hann et al. 1997), which contains a wood quality module that predicts branch size and location along the bole.

Furthermore, logs can be examined on an individual basis, rather than as a batch. While at the batch level reasonable correspondence between actual and simulated lumber recoveries can be found, at the individual log level, differences can be exposed on a board-by-board basis. A number of reasons have been presented to explain the differences: variation in saw patterns, log ori-

The authors are, respectively, Senior Scientist, New Zealand Forest Research Inst. Ltd., Private Bag 3020, Rotorua, New Zealand; Research Team Leader, Ecologically Sustainable Production of Forest Resources, and Forester, Pacific Northwest Res. Sta., USDA Forest Serv., 620 SW Main St., Suite 400, Portland, OR 97205. This study was supported through a Joint Venture Agreement between the New Zealand Forest Research Inst. Ltd. and the USDA Forest Serv., Pacific Northwest Res. Sta. The authors thank the reviewers for their helpful comments. This paper was received for publication in March 2004. Article No. 9868.
*Forest Products Society Member.

Forest Prod. J. 55(6):38-47.

System of coordinates used to locate branches in space

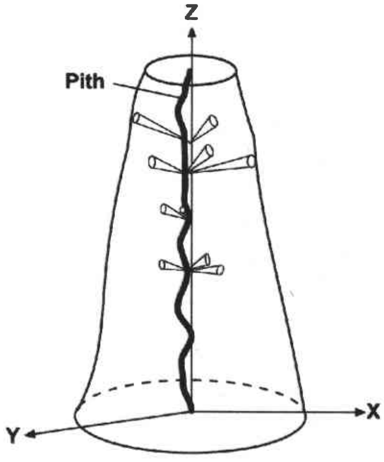

Figure 1. — AUTOSAW log model.

entation, opening faces, knots, and random variability.

Recent technology has allowed for nondestructive scanning of internal features of the log (Oja et al. 2004). Nondestructive tools include gamma rays, x-rays, nuclear magnetic resonance, microwaves, ultrasound, vibration, and longitudinal stress waves. These tools vary in the degree of penetration, scanning resolution, ease of signal interpretation, and cost. In general, the greater the degree of resolution the greater is the opportunity for increased value recovery, but this comes at a greater cost. Fortunately, some knowledge of internal defects, even if imprecise, can provide potential for increased value recovery (Todoroki 2003). Moreover, knowledge of external defects combined with internal interpretation to recreate internal defect structures offers potential to increase value while also eliminating the need for nondestructive tools (Orbay and Brdicko 2001). Like Orbay and Brdicko we also concentrate on surface features and interpret the underlying internal structures. However, rather than generating optimal solutions we compare and contrast sources of measurement error and examine their impact on the resulting grade of sawn boards.

Specifically, we analyze the effect of variation in knot angle (both azimuth and rake, where azimuth is the radial angle and rake the insertion angle) and knot morphology (live or dead), through simulation with the log sawing simulator AUTOSAW (Todoroki 1988, 1997).

Branch angles have not been studied extensively outside of genetic trials. One of the few for Douglas-fir is the detailed branch model of Maguire et al. (1994) and Roeh and Maguire (1997). They predict branch insertion angles as a function of tree size (diameter and height), location in the crown, and site productivity. Roeh and Maguire (1997) found that branches near the top of the crown had an insertion angle approximately 40 degrees from vertical, and that this angle increased nearly linearly to 90 degrees (horizontal) near the bottom of the crown (10 m from the top). This regular progression down the crown to larger, more horizontal branches is a commonly observed morphological characteristic (Kramer and Kozlowski 1979). Hann (1999) modeled Douglas-fir branch angle as a function of branch size and location in the crown. Cluzeau et al. (1994) used a constant branch angle for *Fraxinus excelsior*. Mäkinen and Colin (1998) predicted branch angle in *Pinus sylvestris* as a function of tree diameter and whorl location in the crown; a second model included a distance-dependent competition index (stand density) but was not noticeably superior to the simpler model.

Within the AUTOSAW log-sawing simulator, branches can assume any size and spatial orientation. They emanate from a pith that can deviate from the central log axis. Both live and dead branches are described. A live branch is represented by a right circular cone, and a dead branch by a cylinder concatenated to the end of the cone (Todoroki 1997). Log shape is modeled through a series of independent elliptical cross sections (Todoroki 1988) that permit irregular forms such as crook, sweep, taper, bumps, and kinks. A schematic representation of an AUTOSAW log model is shown in **Figure 1**.

In this study we focus on lumber grade yield from Douglas-fir logs, evaluated according to Western Wood Products Association (WWPA 1998) American Lumber Standards grading criteria. For structural joists and planks, allowable knot size is dependent on a number of criteria, including: 1) branch morphology (unsound or loose knots are equated to dead knots); 2) position relative to edge of board; and 3) board width.

Furthermore, knot size increases proportionately from the size permitted at the edge to the size permitted at the centerline (rather than being constant as is the case for other grading criteria) and is determined by its average dimension as in a line across the width of the piece (perpendicular to the edge).

Methods

Data

Logs used in this validation study were part of a related product recovery study to determine the effectiveness of a proposed log scaling deduction rule for oversized knots. The logs were from trees on the Confederated Tribes of the Warm Springs Reservation in Oregon. They were chosen from a millyard log deck at the Warm Springs Forest Products sawmill in Warm Springs, Oregon. The logs were straight and generally free from obvious external defects, except that some were chosen specifically because they had large knots. The logs varied in length from 3.8 m to 6.5 m, in diameter at the small end (SED) from 150 mm to 358 mm, in taper from 7 to 41 mm/m, and in volume from 0.12 to 0.76 m^3 (**Table 1**).

All visible surface knots of at least 0.5 inch (12.5 mm) in diameter were then mapped and measured on this sub-sample of 28 Douglas-fir logs using log diagramming techniques developed by Barbour et al. (1999). The purpose of log diagramming was to develop digital files of logs that could be repeatedly "sawn" under alternative scenarios and examined with the sawing simulator AUTOSAW (Todoroki 1997). The minimum knot size of 0.5 inch was smaller than the minimum grade deduction for Select Structural, the highest grade (WWPA 1998).

The number of branches that were observed on the log surface ranged from 0 to 71, and mean knot diameter from 0 mm to 55 mm (the mean knot diameter of 0 mm for Log 18 was an artefact of the minimum recording diameter of 12.5 mm; the actual mean was close to 5 mm, judging from photographs). Radial branch angle (azimuth) was recorded for each branch but rake (insertion angle) was assumed to lie perpendicular to the stem. All branches were recorded as being "live" for Logs 1, 4, 5, 9, 18, and 23. The other logs had one or more branches that were recorded as "dead" on the log surface with the transition to "live" occurring within the log at 20 percent of the branch length. This figure was derived after discussions with others involved in knot measurements. The spatial radial distribution of knots about the

Table 1. — Key characteristics of the 27 logs for which sawing was completed.

Log	Length	SED	Taper	Volume	No. of knots	Mean knot diameter	KnotScore
	(m)	(mm)	(mm/m)	(m^3)		(mm)	
1	4.4	150	13	0.12	37	20.4	0.162
2	4.4	152	40	0.22	43	33.9	0.163
3	5.6	160	22	0.23	54	28.6	0.093
4	5.0	166	10	0.15	40	20.7	0.150
5	6.5	166	10	0.23	71	20.5	0.155
6	6.2	172	33	0.42	48	49.2	0.167
7	4.4	178	41	0.26	54	37.2	0.185
8	5.1	178	26	0.26	33	53.0	0.212
9	6.2	180	7	0.21	18	17.3	0.278
10	5.0	186	28	0.29	47	35.1	0.170
11	4.4	194	27	0.24	36	51.3	0.083
12	6.2	200	14	0.29	1	12.0	1.000
13	5.0	204	24	0.30	55	37.1	0.091
14	4.4	210	31	0.29	33	53.7	0.152
15	5.0	216	30	0.37	38	45.3	0.132
16	6.2	216	25	0.44	63	33.2	0.127
17	6.2	218	25	0.46	60	41.3	0.117
18	6.2	226	13	0.34	0	0.0	--
19	6.2	228	23	0.47	45	49.2	0.156
20	5.9	232	14	0.33	9	22.7	0.444
21	6.2	232	22	0.52	57	39.9	0.158
22	6.2	248	28	0.59	46	55.1	0.152
23	6.2	264	26	0.62	59	48.1	0.102
24	6.2	282	10	0.49	49	29.5	0.143
26	5.7	320	8	0.53	29	20.3	0.241
27	3.8	348	22	0.47	34	52.7	0.176
28	5.0	358	26	0.76	29	54.6	0.103

Table 2. — Scenarios developed for positioning knots within virtual logs.

Scenario	Azimuth	Rake	Morphology
1	Original	None	Live and dead
2	Original	Rake model	Live and dead
3	Original ± random error	None	Live and dead
4	Original ± random error	Rake model	Live and dead
5	Original	Rake model	Live only

pith was determined using KnotScore (Barbour et al. 2004), defined as the difference between the maximum and minimum number of knots within each of twelve 30-degree segments divided by the total knot count in the log.

$$KnotScore = \frac{\underset{i=1..12}{Max}(No.Knots_i) - \underset{i=1..12}{Min}(No.Knots_i)}{\sum_{i=1..12} No.Knots_i}$$

KnotScore ranged from 0.091 to 1.000, the former score reflecting a relatively even distribution of branches about the central pith and the latter represented an uneven distribution with only one branch being observed. KnotScore was undefined for Log 18, for which there were no surface branches > 10 mm.

After mapping of knots, the logs were sawn into standard dimension lumber sizes 2 by 4, 2 by 6, or 2 by 8 (39 by 89, 39 by 140, or 39 by 184 mm) and occasional 1-inch-thick boards (19 mm) 4 or 6 inches (89 or 140 mm) wide (in Logs 5, 8, 14, 18, 27, and 28). A Wood-Mizer portable sawmill (www.woodmizer.com/welcome.html) was used to saw the logs. The use of this machine made it possible to maintain dependable product identification throughout the processing. As the opening cut was begun, the log end was photographed showing the position of the zero reference line that was established during the knot mapping. During sawing, a cutup diagram was rendered, and each board was marked on its surface with respect to its position in the diagram. In addition, the boards from each log were arranged on wood bunks and photographed on both sides to aid in checking of possible errors in recording.

The lumber produced from these logs was combined with lumber from 16 other logs sawn by the Wood-Mizer and 143 logs sawn in the Warm Springs Forest Products sawmill. All the lumber from the product recovery study was combined, and dried along with the mill's normal production. After drying, the lumber was planed and graded by certified WWPA graders employed by the mill in the presence of a WWPA grading inspector. All 2-inch-thick lumber was graded according to WWPA (1998) framing grading criteria. In addition, sawing diagrams had been mapped, and for seven logs (Logs 4, 8, 11, 20, 26, 27, and 28) were complete with grades. Other sawing diagrams were also reconstructed by matching recorded board ID to the sawing pattern. The sawing of Log 25 was not completed as the sawyer encountered difficulty with that log, the sawblade stopped, and heavy pitch and incipient decay were noted. For these reasons, Log 25 has been removed from all results and analysis.

Log models

For each of the 27 logs, 5 virtual models (scenarios) were created (**Table 2**): one simulating the branching conditions as initially recorded (i.e., field measurement of azimuth, assuming no rake, and visually assessed live/dead knot morphology), one incorporating the rake model with the field measurement of azimuth and live/dead knots, one simulating measurement error on azimuth (and no rake with live/dead knots), and one incorporating both measurement error on azimuth and the rake model (with live/dead knots). The fifth scenario examined the effect of branch morphology on lumber grade, and assumed all knots to be live. The five azimuth-rake-morphology scenarios are shown in **Table 2**.

To estimate and simulate measurement error, additional knot data were collected, analyzed, and knot azimuth and rake models were developed as follows.

Knot azimuth

In the field, knot azimuth had been measured to the nearest 5 degrees. Consequently, the measurement error associated with azimuth was set to within half this interval (i.e., to ± 2.5 degrees). A random number generator that generated numbers 0 to 10, associated with measurement errors of -2.5 to +2.5 in 0.5-degree increments, was used and the resultant measurement error added to the original azimuth reading.

Knot rake model

Knot rake, or insertion angle, had not been recorded in the field. To develop a model for predicting knot rake, additional field measurements were required. Data were collected from two sites: one was a densely populated stand while the other was widely spaced. Measurements of knot rake and size were made from digital images of Douglas-fir trees selected from two sites and analyzed using SigmaScan Pro 5.0 image analysis software (www.statsol.ie/sigmascan/sigmascan.htm). The measurements suggested that spacing affected rake. In dense stands, knot rake was normally distributed with a mean of 65 degrees measured from vertical, and standard deviation of 14 degrees. In the more open arrangement where more light could get through and branches were larger, the mean and standard deviation were 99 and 10 degrees, respectively. Therefore, two models were developed to represent the densely packed and widely spaced stands. The latter model was used to estimate knot rake for logs in the 5- to 10-inch-diameter range (12.7 to 25.4 cm) containing live knots larger than 2 inches (50.8 mm), or dead knots larger than 1 inch (25.4 mm), and for logs 11 to 20 inches in diameter (27.9 to 50.8 cm) that contained live knots larger than 3 inches (76.2 mm) or dead knots larger than 2 inches (50.8 mm). Knot rake for all other logs was estimated using the former model.

Within each log, branch rake was randomly allocated. With the introduction of rake to the branch model, the length of each branch was extended using trigonometric relationships between branch angle and log taper to ensure that the branch ended at the log surface. The ratio of live to dead branch was maintained as was knot size at the log surface.

Sawing simulations

Saw patterns that approximated those used in the actual empirical studies were created using the AUTOSET module of the AUTOSAW system (Todoroki 1997). To emulate a 0.055-inch (1.4-mm) Wood-Mizer sawkerf, a 2.1-mm kerf that added 50 percent to the kerf for heat and vibration was specified. Cant depth was 156 mm deep (6 inches) for logs with an SED of 161 mm or more (6.3 in.) and 99 mm (4 in.) for smaller logs (i.e., Logs 1, 2, and 3). Board thickness was prescribed at 45.2 mm (2 in.) and width as 99 and 156 mm (4 and 6 in.). Note that these dimensions allowed for sawing variation, drying shrinkage, and planing to reach the nominal WWPA board sizes (39-mm-thick for Structural grades and 37 mm for Shop appearance grades). An automated edging procedure that could produce two edged pieces from the wider boards and maximized volume was invoked. Up to a maximum of 20 mm of wane was permitted on the edges of each piece. Log orientation was unique to each log, having been selected to replicate the placement of the orientation of the real log at the sawmill. Original sawing orientation was accomplished by photographing the log end as the first cut was made on the log. At the time of knot mapping, a radial position reference line was drawn on the log end. The position of this reference line in the photograph, in degrees, was used as a rotation parameter. The saw patterns were repeated for each of the knot scenarios. Note that each set of knot scenarios, while producing identical flitch and board sizes, could differ in the size and position of knots on the board surfaces.

Grading criteria

Boards were automatically graded according to knot size using WWPA (1998) criteria for Structural Light Framing for grading the 2 by 4 boards (WWPA chapter 42.00), and Structural Joists and Planks for grading the 2 by 6 and 2 by 8 boards (WWPA chapter 62.00). Knot size was determined by its average dimension perpendicular to the edge of the piece. Allowable knot size increased proportionately from the size permitted at the edge to the size permitted at the centerline. Allowable edgeline and centerline sizes are dependent on board width (WWPA 1998). In accommodating the grading criteria within AUTOSAW, a procedure that determined the size, displacement, and morphology of knots on both board faces was developed. The displacement of the knot was assumed to be the minimum distance between the knot (on either face) and the closest board edge. Using that displacement, the allowable scaled knot size was calculated. Thus any knot that touched the edge was an edgeknot and the edgeline criteria applies.

Boards were color-coded to reflect lumber grade. The five grades within each category, from the highest to the lowest grades, were yellow, orange, red, brown, and black, respectively (**Fig. 2**). As only 2-inch thick boards were simulated, the occasional piece of actual lumber that was less than 2 inches thick was excluded from the analysis, and depicted using a hatched pattern. This mill, in their normal operating procedures, avoided cutting 1-inch boards for lack of a market. Furthermore, the occasional Lam Stock board was counted as a Select Structural board.

Note that both the sawing simulation and the actual empirical sawmill study yielded framing lumber grades ranging from Select Structural to Economy. However, none of the boards from the 27 logs was graded No. 1 by the mill's WWPA graders.

Log quality assessment through lumber quality descriptors

For each log, a grade that reflected average lumber quality was defined. A grade-weighted average was calculated by computing the ratio of total weighted lumber volume of each grade to total lumber volume. A weight of 5 was assigned to Select Structural grade lumber, 4 to No.1, 3 to No.2, 2 to No. 3, and 1 to Economy. In this way, a log that comprised only Select Structural grade lumber would score 5.0 (i.e., a Select Structural log) while a log comprising only Economy lumber would score 1.0.

$$\textit{Grade Average} = \frac{\sum (WEIGHT_{[grade]} \times VOLUME_{[grade]})}{\sum VOLUME_{[grade]}}$$

A *grade change* was said to occur if the grade of a board within a given log differed under any of the simulated scenarios. Log quality was assessed using each of these methods for the simulated scenarios and for the actual sawn lumber.

Results

Grade distributions obtained from the 27 logs under each of the simulated sce-

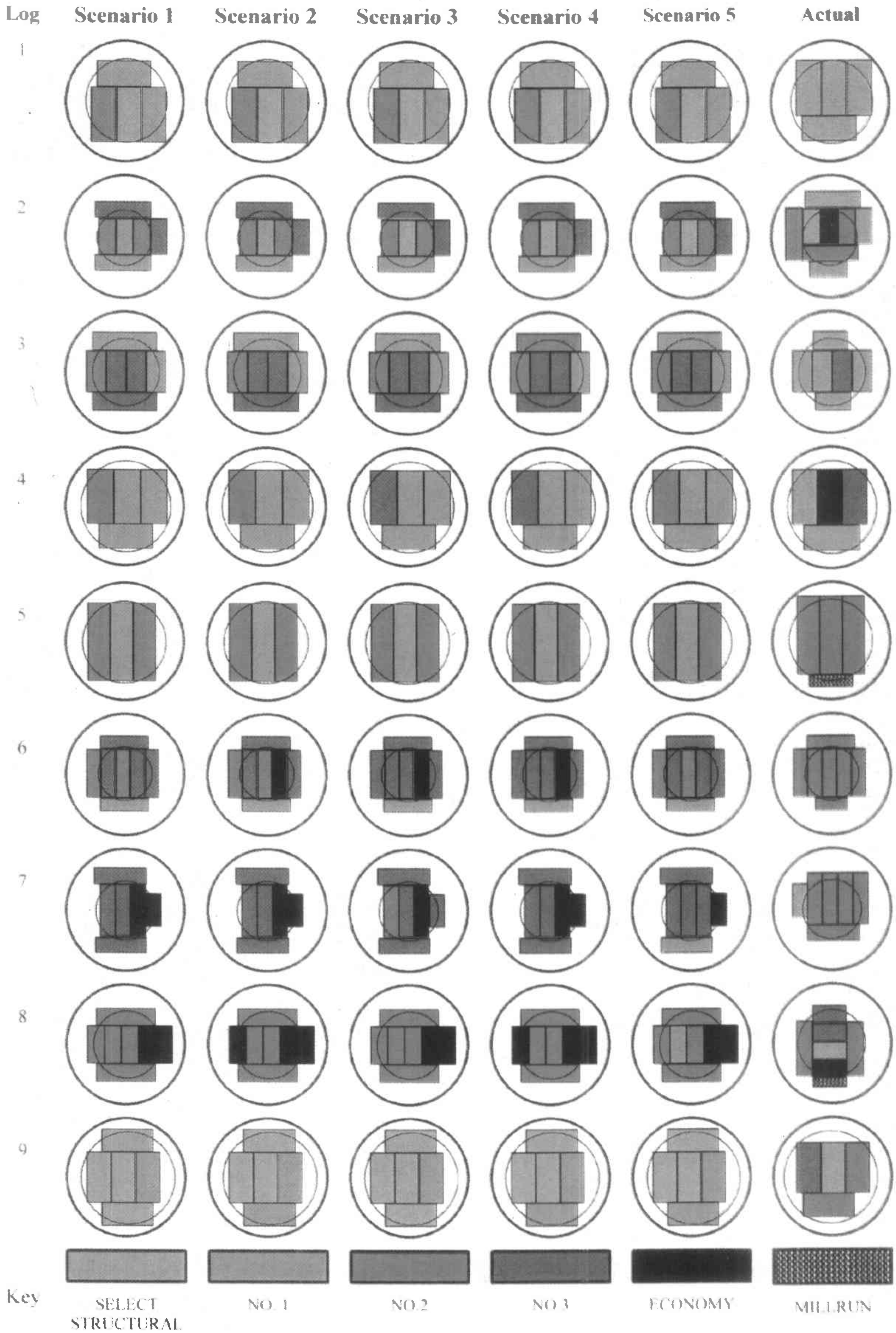

Figure 2. — Sawing patterns and lumber grades; the outer circle represents the large end of the log and the inner circle represents the small end.

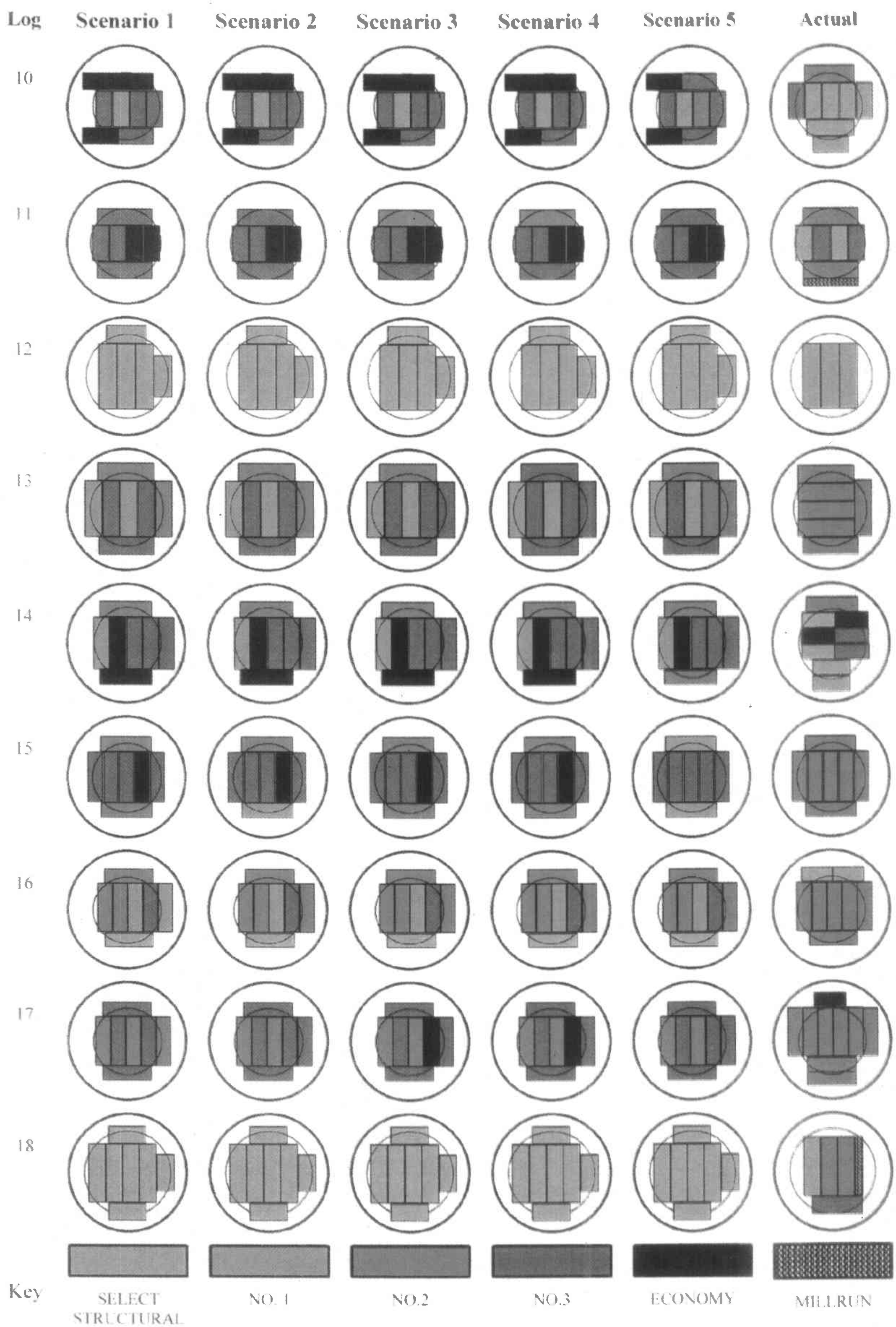

Figure 2. — Sawing patterns and lumber grades; the outer circle represents the large end of the log and the inner circle represents the small end (continued).

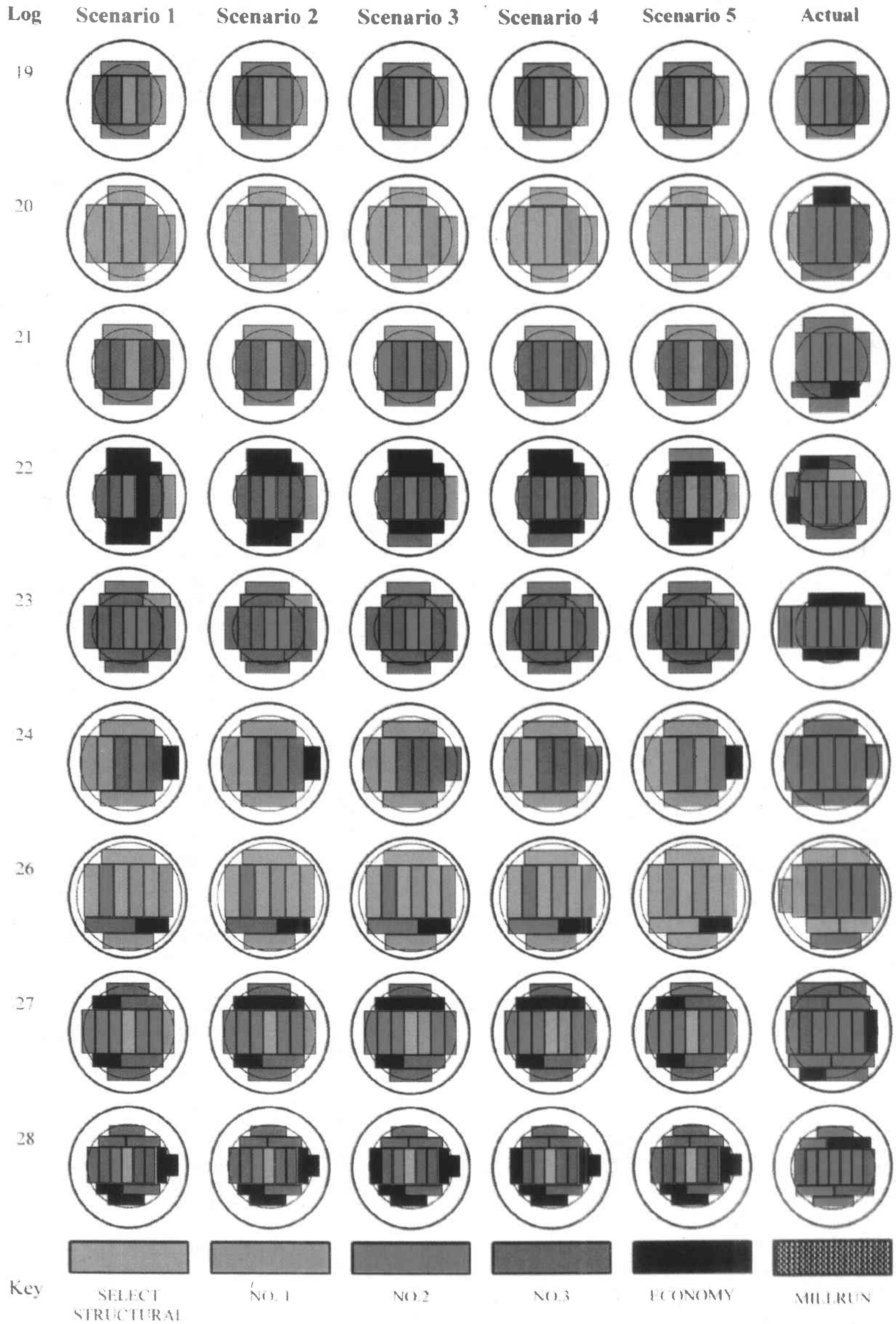

Figure 2. — Sawing patterns and lumber grades; the outer circle represents the large end of the log and the inner circle represents the small end (continued).

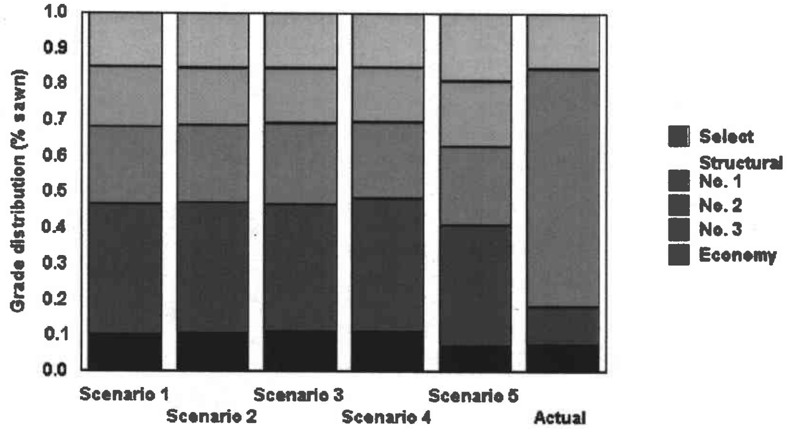

Figure 3. — Grade distributions from 27 Douglas-fir logs simulated with various knot structures.

narios (each with identical saw patterns) and from the actual empirical study are shown in **Figure 3**. The proportion of Select Structural lumber was 15.3 percent for Scenarios 1 and 4, 15.6 percent for Scenarios 2, 3, and the mill study, and 19.1 percent for Scenario 5. On the other hand, the proportion of Economy lumber was nearly the same for Scenarios 5 and the mill study (7.1% and 7.3%, respectively), but ranged from 9.9 to 11.1 percent with the other scenarios. The greatest difference was in the proportion of intermediary grades. In the mill study, none of the boards was graded as No.1, and the majority were graded as No. 2. Of the simulation scenarios, the greatest difference was with Scenario 5 (all branches simulated as live), which recorded the greatest volumes of Select Structural and No. 1 lumber.

Of the total 200 simulated boards, one quarter (26.5%) recorded a grade change between scenarios. With only small changes in azimuth, and all other factors held constant, 25 boards differed in the comparison between Scenarios 1 and 3, and 23 boards differed in the comparison between Scenarios 2 and 4. Smaller differences were noted with changes in rake only: 10 boards changed grades when comparing Scenarios 1 and 2, and 6 changed when comparing Scenarios 3 and 4. With changes to both azimuth and rake (Scenarios 1 vs. 4), 27 grade changes were noted. With changes in morphology only (Scenarios 2 vs. 5), 28 grade changes were recorded; with morphology and rake (Scenarios 1 vs. 5) 31 grade changes; morphology and azimuth (Scenarios 4 vs. 5) 46 grade changes; and morphology, azimuth, and rake (Scenarios 3 vs. 5) also had 46 grade changes.

While in most cases the shift in board grade was either one grade higher or lower, in some cases shifts of two or three grades were recorded (e.g., Logs 20 and 26; see **Fig. 2**). Of the 27 logs, 5 were invariant (Logs 1, 5, 12, 18, and 19) under all scenarios. In the case of Log 2, one of the six boards recorded different grades across the scenarios. For Log 3, two of the six boards recorded different grades, and for Log 7, four of the six boards recorded a grade change.

Overall, Scenarios 1 through 4 recorded a Grade Average of 3.0, while both Scenario 5 and the mill study recorded a Grade Average of 3.2 (**Table 3**). On an individual log basis, actual Grade Average was the same as simulated Grade Average (to one decimal place) across all scenarios for Log 12, which had one surface knot of 12 mm diameter. However, for Log 18, with no surface knots, actual and simulated Grade Average differed significantly. Simulations with the knot-free Log 18 model produced knot-free Select Structural lumber, with a corresponding Grade Average of 5.0 across all scenarios. These results were expected and are consistent with grading criteria for knot-free boards (WWPA 1998). However, actual sawn lumber yielded a 3.3 Grade Average in the mill study. The actual lumber recorded in the field contained the following lumber grade mix: Lam Stock (one board, counted as if Select Structural), No.2 (two boards), No.3 (one board), and Millrun 4/4 (one board, excluded).

In addition to Log 12, a further seven logs (Logs 8, 13, 16, 21, 23, 24, 26) were within 0.1 units of the actual results for at least one of the simulation scenarios. Eight more logs (Logs 2, 4, 5, 6, 17, 19, 22, 27) were within 0.5 units, and a further four logs (Logs 1, 14, 15, 28), giving a total of 20 logs (of the 27), were within 1 unit of the actual Grade Average. Of the remaining logs, the simulated scenarios under-predicted lumber grade in four cases (Logs 3, 7, 10, 11) and over-predicted in three cases (Logs 9, 18, 20). Logs 3, 7, 10, and 11 were all small logs (SED less than 200 mm) containing dead knots of at least 30 mm in diameter. Each of Logs 9, 18, and 20 had a very low number of knots on the log surface (18, 0, and 9 knots, respectively). In addition, Logs 9 and 20 had highly uneven branch distributions (cf. KnotScores of 0.278 and 0.444, respectively).

In general, Grade Average decreased with increasing mean knot diameter. This tendency was stronger for simulated grade yield (r^2 ranging from 0.73 to 0.75) than actual grade yield (r^2 = 0.25). The relationship between actual and simulated Grade Average was quite poor (r^2 ranging from 0.09 to 0.11).

Discussion

The simulation exercises have demonstrated the sensitivity of lumber grade to small changes in knot angle and/or morphology. A change of one grade, either up or down, was not uncommon, and affected more than one quarter of all boards overall. The change in quality over time associated with branches can be thought of as a step function where knot-free straight-grained (clear) wood is the best quality and wood containing dead loose (black) knots or holes is considered the worst quality (i.e., clear wood > live knots > tight dead knots > loose black knots or knot holes) (Barbour et al. 2002). This step function is firmly ingrained in the logic used in developing the WWPA (1998) lumber grading rules (Barbour et al. 2002).

The effect of azimuth on grade change was greater than that of rake, and the effect of morphology was greater still. The change in morphology from dead to live was estimated at 20 percent. If the dead proportion of the branches was reduced to less than 20 percent then the results of Scenarios 1 through 4 would be closer to Scenario 5 (0% dead). However, if the dead proportion of the branches were increased beyond 20 percent then the proportion of higher grades would be expected to decrease and the lower grades to increase. Had the position of the logs within the trees or height above the ground been known,

Table 3. — Lumber quality descriptors, Grade Average, for each of the simulated knot scenarios and actual lumber yield.

Log	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Actual
1	4.0	4.0	4.0	4.0	4.0	5.0
2	3.1	3.1	3.3	3.3	3.6	3.5
3	2.7	2.7	2.7	2.6	2.9	4.4
4	3.7	3.7	3.4	3.4	3.7	3.1
5	3.4	3.4	3.4	3.4	3.4	3.0
6	2.5	2.3	2.0	2.0	2.5	3.0
7	1.7	1.7	2.0	1.8	2.1	3.2
8	2.6	2.4	2.6	2.4	2.7	2.7
9	4.8	4.6	4.8	4.6	4.6	3.1
10	2.1	2.1	2.1	2.1	2.3	4.4
11	1.7	1.7	1.9	1.9	1.7	3.3
12	5.0	5.0	5.0	5.0	5.0	5.0
13	2.8	2.8	2.7	2.6	3.0	3.0
14	2.1	2.1	2.1	2.1	2.4	3.2
15	2.1	2.2	2.1	2.1	2.5	3.0
16	3.3	3.2	3.2	3.2	3.2	3.4
17	2.4	2.3	2.2	2.2	2.3	2.9
18	5.0	5.0	5.0	5.0	5.0	3.3
19	3.0	3.0	3.0	3.0	3.0	2.7
20	4.8	4.6	4.8	4.8	5.0	2.5
21	2.7	2.7	2.8	2.6	2.7	2.7
22	1.8	1.9	2.0	2.0	2.4	2.7
23	2.4	2.4	2.3	2.3	2.4	2.4
24	3.1	3.1	3.1	3.1	3.7	3.0
26	3.9	4.0	4.0	4.0	4.5	3.8
27	2.7	2.7	2.7	2.7	2.8	2.5
28	2.1	2.1	2.0	2.0	2.1	2.7
Mean	3.02	2.99	3.01	2.97	3.17	3.24

then this information could have been incorporated to develop a live/dead ratio that varied with height and provided a closer representation to tree physiology. Within the simulator, the change in morphology is reflected by a change from a cylindrical to a conical representation in the branch model. This in turn creates a smaller knot cross section when crosscut, and together with the more lenient requirements for live knots, produces higher grades. The size of the knot cross section would also differ had other knot representations been modeled. Here the knot axis is assumed to be straight (i.e., a right circular cone). In reality, the central axis of the knot can be seen to bend over time. The angle between the stem and upper side of a branch is initially small, but it increases with age due to increasing branch weight (Jacobs 1938).

In general, logs with large surface knots (mean knot diameter greater than 40 mm) had low Grade Averages for both simulated (ranging from 1.7 to 3.0) and actual lumber (ranging from 2.4 to 3.3). However, the converse was not always true. For example, Log 20 with an average knot diameter of 22.7 mm, had an actual Grade Average of 2.5, well below the predicted average of 4.8. Log 18, with no surface knots, had an actual Grade Average of 3.3, but a simulated average of 5.0. Digital photos of the boards sawn from Log 18 reveal a normal number of knots that are all less than 10 mm diameter, well below any grade deduction; no other visible defects can be seen, except for rather minor splitting at the end of a few boards. Clearly, there are other factors not represented in this study that have an additional significant effect on lumber grade.

Lumber graders have many board characteristics to consider before making a decision about a lumber grade. According to the WWPA criteria (American Lumber Standards), structural joists and planks are graded dependent on severity or frequency of the following conditions: knots, pitch and pitch streaks, shake, planer skip, slope of grain, splits, stain, wane, and warp. Some of these conditions are inherent in the wood, and others are a result of the sawing, drying, or planing process.

AUTOSAW grades a board based on knots and wane. It is able to grade according to whether the knot is live or dead, its location on the face or edge of the board, and knot size in relation to the width of the board. Information regarding post-processing of the boards (e.g., drying and planing) is not available to AUTOSAW. In this study, the actual grades of boards were determined after this post-processing. Had the rough green lumber been graded at the mill, the difference between actual and simulated may have been reduced and a closer correspondence obtained. Conversely, additional rules could be incorporated in the simulator to, for example, prevent heart centers or juvenile wood being assigned to the highest grades. Such wood quality characteristics and other lumber defects that are not currently represented in the simulated log would probably resolve much of the difference in grade recovery between actual and simulated sawing. Identification and isolation of those additional degrading features is an important step in understanding those critical features and threshold levels that contribute to lower lumber grades. This in turn will facilitate the development of methods for predicting lumber quality within logs.

Clearly, a large number of defects exist beyond the various knot deductions simulated by AUTOSAW. Modeling knots is necessary for accurate grade recovery prediction. However, this study has shown that knowledge of the external log and knot features alone is not sufficient for accurate prediction of lumber grade.

Literature cited

Barbour, R.J., D.D. Marshall, D.L. Parry, and G.A. Christensen. 2002. Do large trees always have higher wood product value? Chapter 14. *In*: Proc. of the Wood Compatibility Initiative Workshop. A.C. Johnson, R.W. Haynes, and R.A. Monserud, eds. Gen. Tech. Rept. PNW-GTR-563. USDA Forest Serv., Pacific Northwest Res. Sta., Portland, OR. pp. 135-144.

__________, E.C. Lowell, C.L. Todoroki, D.L. Parry, and G.A. Christensen. 1999. Simulating North American lumber grade recovery with AUTOSAW using externally visible branch and stem form characteristics. *In*: Proc. of the Third Workshop on the Connection Between Silviculture and Wood Quality Through Modeling. G. Nepveu, ed. IUFRO WP 5.01-

04. Biological improvement of wood properties. Instruments Regent Inc., Rue Blain, France. pp. 493-504.

__________, D.L. Parry, C.L. Todoroki, G.A. Christensen, and E.C. Lowell. 2004. Within and between log variation in lumber grade yield as demonstrated using AUTOSAW. *In*: Proc. of the Fourth Workshop on the Connection Between Silviculture and Wood Quality through Modelling Approaches and Simulation Softwares. G Nepveu, ed. IUFRO S5.01-04. Publication Equipe de Recherches sur la Qualite des Bois (Wood Quality Research Team). INRA (National Institute of Agricultural Research). Nancy, France. pp. 450-455.

Cluzeau, D., N. LeGoff, and J-M. Ottorini. 1994. Development of primary branches and crown profile for *Fraxinus excelsior*. Can. J. of Forest Res. 24:2315-2323.

Cown D.J., D.L. McConchie, and C. Treloar. 1984. Timber recovery from pruned *Pinus radiata* butt logs at Mangatu: Effect of log sweep. New Zealand J. of Forestry Sci. 14(1): 109-123.

Fahey, T.D., J.M. Cahill, T.A. Snellgrove, and L.S. Heath. 1991. Lumber and veneer recovery from intensively managed young-growth Douglas-fir. Res. Pap. PNWRP-437. USDA Forest Serv., Pacific Northwest Res. Sta., Portland, OR. 25 pp.

Hann, D.W. 1999. An adjustable predictor of crown profile for stand-grown Douglas-fir trees. Forest Sci. 45:217-225.

__________, A.S. Hester, and C.L. Olsen. 1997. ORGANON user's manual edition 6.0 incorporating: Southwest Oregon version and western Willamette Valley version. Dept. of Forest Resources, Oregon State Univ., Corvallis, OR.

Jacobs, M.R. 1938. Notes on pruning *Pinus radiata*. Part 1. Observations on features which influence pruning. Bulletin No. 23. Commonwealth Forestry Bureau, Canberra, Australia. 47 pp.

Kramer, P.J. and T.T. Kozlowski. 1979. Physiology of Woody Plants. Academic Press, Inc., New York. 811 pp.

Maguire, D.A., M. Moeur, and W.S. Bennett. 1994. Models for describing basal diameter and vertical distribution of primary branches in young Douglas-fir. Forest Ecol. and Management 63:23-55.

Mäkinen, H. and F. Colin. 1998. Predicting branch angle and branch diameter of Scots pine from usual tree measurements and stand structural information. Canadian J. of Forest Res. 28:1686-1696.

Oja, J., S. Grundberg, J. Fredriksson, and P. Berg. 2004. Automatic grading of saw logs: A comparison between X-ray scanning, optical three-dimensional scanning and combinations of both methods. Scandinavian J. Forest Res. 19:89-95.

Orbay, L. and J. Brdicko. 2001. Using external log characteristics for stem and log breakdown optimization. *In*: Proc. ScanTech 2001. Ninth Inter. Conf. on Scanning Tech. and Process Optimization for the Wood Industry. Wood Machining Inst., Berkeley, CA.

Roeh, R.L. and D.A. Maguire. 1997. Crown profile models based on branch attributes in coastal Douglas-fir. Forest Ecol. and Management 26:77-100.

Todoroki, C.L. 1988. SEESAW: A visual sawing simulator, as developed in version 3.0. New Zealand J. of Forestry Sci. 18(1)116-123.

__________. 1997. Developments of the sawing simulation software, AUTOSAW: Linking wood properties, sawing, and lumber end-use. *In*: Proc. of the Second Workshop on the Connection Between Silviculture and Wood Quality through Modeling Approaches and Simulation Softwares. IUFRO S5.01-04. G. Nepveu, ed. Publication Equipe de Recherches sur la Qualite des Bois, (Wood Quality Research Team), INRA (National Institute of Agricultural Research), Nancy, France. pp. 241-247.

__________. 2003. Accuracy considerations when optimally sawing pruned logs: Internal defects and sawing precision. Nondestructive Testing and Eval. 19:29-41.

Whiteside, I.D. 1982. Predicting radiata pine gross sawlog values and timber grades from log variables. FRI Bull. No. 4. New Zealand Forest Service. Forest Res. Inst., Rotorua, New Zealand.

Whiteside, I.D. 1990. STANDPAK modelling system for radiata pine. *In*: Proc. IUFRO Conf. New Approaches to Spacing and Thinning in Plantation Forestry. R.N. James and G.L. Tarlton, eds. FRI Bull. No. 151. Ministry of Forestry, Forest Res. Inst., Rotorua, New Zealand.

Western Wood Products Association (WWPA). 1998. Western lumber grading rules '98. WWPA, Portland, OR. 248 pp., plus supplements.