Wood Quality of Old-Growth Koa Logs and Lumber

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Abstract

Acacia koa trees are ecologically, economically, and culturally significant to the Hawaiian Islands. Koa wood is one of the most valuable species in the world and sale of koa products represents a majority of all the Hawaiian wood products sold by Hawaiian retailers. Today, there is concern in Hawaii among foresters, forest landowners and managers, wood products manufacturers, and the public that the remaining old-growth koa resource has become scarce, is suffering from declining health and diseases, and is characterized by poor growth form. Current practices require harvest of only dead and dying trees and using downed material in wood products manufacturing. We examined lumber volume and value recovery from logs sawn from dead and dying trees and from relic logs (logs that have been on the ground) from four sites on the island of Hawaii. Gross lumber recovery from all study logs was 71 percent. Log size did not significantly influence lumber volume recovery. Forty-five percent of the lumber manufactured from relic logs was below grade compared with 26 percent of the lumber sawn from standing dead and dying trees. Variables that affect lumber quality, such as different defects and heartwood proportion, were measured. Decay-type defects were the most prominent.

Koa (*Acacia koa* A. Gray) is a tree species that is endemic to the islands of Hawaii—the only place it grows worldwide. It is an important legacy species ecologically, culturally, and economically. Koa wood was used by Hawaiian natives for centuries for a variety of essential and culturally significant purposes, the most celebrated of which is the Hawaiian canoe. It is written that Captain Cook reported seeing 1,000 canoes in one bay on the west side of the island of Hawaii during his visit there in 1779 (Cuddihy and Stone 1990).

Today, koa is used for a wide range of appearance products—furniture, cabinets, and flooring—as well as for art pieces, instruments (principally guitars and ukuleles), bowls, picture frames, and other small craft items. Koa products were estimated to make up 75 percent of the total value of all Hawaiian grown wood products sold by Hawaiian retailers in 2001 (Friday et al. 2006), contributing an estimated $18 million to the Hawaiian economy. Close to 10 percent of all manufacturing concerns in Hawaii in 2012 were centered on wood (e.g., sawmills) or wood products (e.g., kitchen cabinets and flooring). Most of these were small manufacturers having a workforce of fewer than five people (US Census 2015).

Koa is one of the most valuable timber species in the world. While the quality of the wood is ultimately defined by the consumer and many koa markets are niche markets, the following value generalizations apply: (1) highly figured log sections are sold to artisans who make carvings, sculptures, artistic bowls, and furniture—these are extremely variable in value; (2) full-curl koa lumber sells in the range of $65 to $150 per board foot with the higher prices associated with wider lumber (22.9 cm or 9 in., minimum) that meets instrument quality specifications; (3) the highest-value cants, usually containing a significant amount of curl for manufacture into veneer, can have a value in the $60 to $75 per board foot range; and (4) koa lumber with unremarkable color and figure will sell for between $1.62 per board foot for flooring and $11.35 per board foot for furniture and millwork (Caldwell 2009, and personal communication with sawmill cooperators in 2007 and 2011).

There is much concern in Hawaii among foresters, landowners and managers, wood products manufacturers, and the public that the remaining old-growth koa (naturally occurring, mature trees, typically 80 yr or older) resource has become scarce and is characterized by poor growth form and poor health. Current regulations require harvest of only dead and dying trees and using downed material in wood products manufacturing. Standing trees tend to be eccentric in shape with significant fluting in the basal zone.

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Significant amounts of rot are found in a large proportion of these trees, but external defect indicators are absent (Baker et al. 2009). Large limbs branch off at low heights up the main stem, creating what is referred to as an ''apple tree'' form (Friday 2010). Volume equations for these trees are difficult to apply or poorly validated (Baker et al. 2009). Downed material that was rejected and left on-site during previous harvests is now being collected and processed. Log scaling, cull estimation, and lumber recovery and grade predictions have not been fully developed and implemented for *A. koa* owing to the highly variable nature of trees and logs. Also, because the value of koa wood is highly dependent on the color of the heartwood and whether curly figure is present, these potentially have a larger influence on the value of koa stems than does grade and volume of lumber recovered in sawing. Stumpage sales of koa timber today range between \$3 and \$4 per board foot (Scribner scale; Elevitch et al. 2005, Friday 2010), but many contracts between private landowners and loggers/sawmillers contain adjustment provisions that are based on the value of lumber sawn from the logs.

An effort was made by Burgan et al. (1971) to establish a koa-specific system for volume and cull estimation in koa sawlogs. The evaluation produced preliminary guidelines for log volume adjustments associated with several defects. Unfortunately, the number of samples of each type of defect was very small (e.g., the only defect type with a sample size exceeding 10 observations was ''hole''). For this reason, the scaling factors of Burgan et al. (1971) were never adopted.

Lowell et al. (2013) provide a different approach for foresters, landowners, and loggers to use in evaluating the potential value of koa logs. Their work serves as a tool for understanding the extent and influence of various external defect indicators on koa lumber volume and value recovery.

The objectives of this study were the following:

1. to evaluate koa lumber volume and grade recovery for logs from multiple sites on the island of Hawaii;
2. to examine volume and grade recovery differences for koa logs from standing dead and dying timber compared with logs that have been lying on the ground for more than a year (relic logs);
3. to detect differences in defect occurrence rates between sites; and
4. to explore relationships between log diameter, site, and heartwood content of logs and lumber.

Materials and Methods

Study log origins (sites, types, and sample selection)

Log and lumber data were collected at four locations on the island of Hawaii (Fig. 1). These locations were selected based on recommendations of local agency representatives and addressed site differences and origin. Origin refers to the two type of logs that were sampled: those that came from standing dead and dying trees and logs that had been on the ground for an undetermined amount of time (years). The downed logs, referred to as relic logs, had been discarded in the past as not being worth processing and had been on the ground for an unknown number of years (at least one), but in all cases long enough for the sapwood to rot and decompose (Fig. 2). Site 1, on the west side (leeward side) of the island, was the source of a unique set of relic logs. Two study sites (Sites 2 and 3) were on the east side (windward side) of the island. Site 2 represented an existing sale of standing dead and dying trees on the Department of Hawaiian Homelands land. The site was at about 1,830 m (6,000 ft) elevation on the Mana Road off Saddle Road, where the mean annual temperature is 53°F (11.7°C) and nighttime temperatures during winter occasionally fall to 25°F (–4°C). Average annual rainfall in this area is about 100 to 150 inches. Native montane forests merge into abandoned pasturelands at this elevation, where there exists an abundance of nonnative grasses and weeds (US Fish and Wildlife Service [USFWS] 2010). Sample trees represented the diameter at breast height distribution of the trees to be harvested. A total of seven butt logs were processed from Site 2. Logs from Site 3, in the northeast portion of the island, were from dead and dying trees growing at an elevation of 1,340 m (4,400 ft). This site was close to Site 2, but because of temperature inversions that occur on the windward side of Mauna Kea, the lower-elevation Site 3 koa forest tends to receive considerably more rain (USFWS 2010). Manufacturing time constraints limited the sample to only two logs from the log deck at Site 3. Nine logs were selected from the log deck at Site 4, a sawmill operation on the west side of the island. Average annual rainfall at this location on the leeward side of the island is much lower than for Sites 2 and 3—fewer than 50 inches per year. The log deck at Site 4 contained logs harvested from standing dead and dying trees that were growing at elevations between 915 and 1,220 m (3,000 and 4,000 ft). A summary of sample data can be found in Table 1.

Log and defect measurements

Extensive data were collected for each of the 24 study logs to allow for examining correlations between different koa log quality attributes and defects and the volume and value of lumber recovered from the logs. Data collected included large- and small-end log diameters inside bark to the nearest 2.5 mm (0.1 in.), log length measured to the nearest 0.03 m (0.1 ft), defect types and dimensions (including estimated depth of penetration into logs) of both end and face defects, and the position of each defect along the log's length and its azimuth. To limit variation, the same person made the defect determinations for all logs.

Log scale

The Patterson and Doruska modification of Smalian's log volume equation (Patterson and Doruska 2004) was used to calculate each log's gross cubic foot volume. This modified equation has been shown to be more accurate than the unmodified Smalian's equation for butt logs (Patterson et al. 2007). This is particularly true for species that tend to flare in the basal region, as is true for *A. koa*. Scale deductions (volume deductions) were based on the presence, location, and size of scalable defects—decay, mechanical damage, branches, ring shakes and heart checks, crook and sweep, and net log volume calculated. As logs were closely examined and measured for defects, scaling deductions were more precise than production scaling. Scaling deductions were made using Rast et al. (1973) and Grosenbaugh (1952) as references.

Most, but not all, logs sawn in this study were butt logs. Given the value of koa and the fact that butt logs of trees will have a higher proportion of heartwood and fewer limbs than upper logs, butt logs are seldom left behind. As the

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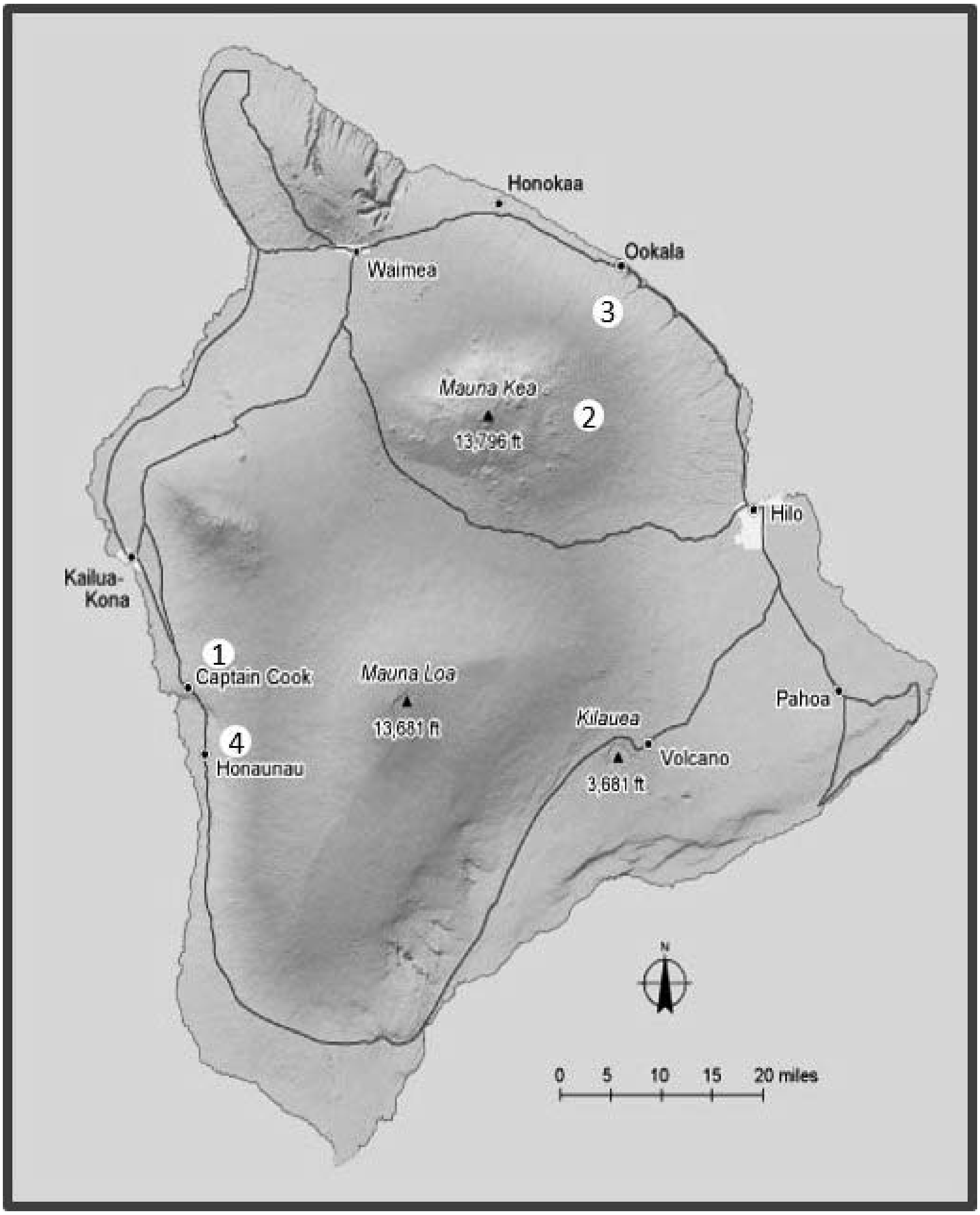

Figure 1.—Island of Hawaii with site locations.

relic logs were retrieved from the ground, the position in the tree from which these logs were bucked could not be determined with certainty. It is possible that some of these logs may have been upper logs rather than butt logs. However, the diameters and lengths of the relic logs were similar to logs from other sites (Table 1).

Log heartwood percent

Because it is the heartwood of koa that is valued for high-end product manufacture, heartwood diameters of both the large and the small ends were measured to the nearest 0.25 mm (0.1 in.) for each log. The cubic foot volume of the

Table 1.—Data for log samples from four sites.

Log source	Elevation, ft (m)	Log type	No. of logs	Range of log small-end diameters, in. (cm)	Range of log large-end diameters, in. (cm)	Range of log lengths, ft (m)
Site 1	4,900 (1,493.52)	Relic	6	12–37 (30.48–93.98)	13–37 (33.02–93.98)	5–11 (1.58–3.38)
Site 2	6,000 (1,828.80)	Standing dead/dying	7	16–32 (40.64–81.28)	20–34 (50.80–86.36)	5–9 (1.71–2.90)
Site 3	4,400 (1,341.12)	Standing dead/dying	2	8–14 (20.32–35.56)	14–17 (35.56–43.18)	7–7 (2.19–2.29)
Site 4	1,200 (3,65.76)	Standing dead/dying	9	13–29 (33.02–73.66)	18–34 (45.72–86.36)	8–13 (2.44–4.18)

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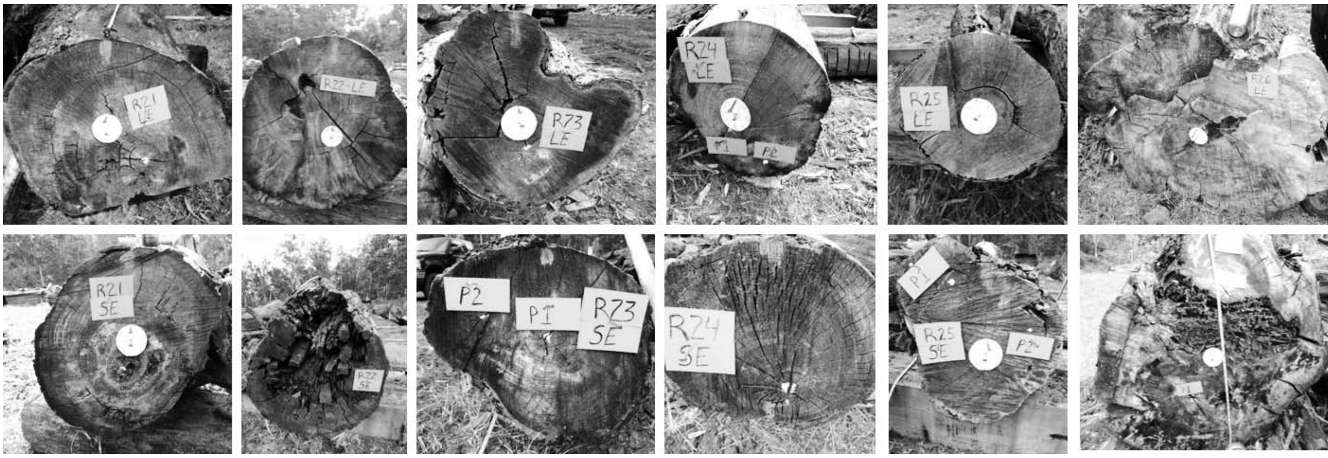

Figure 2.—Site 1 relic log ends with large ends (LE) shown in top row and small ends (SE) shown in bottom row. Note degree of decay and checking on many, but not all, log ends.

heartwood cylinder was calculated using the Patterson and Doruska (2004) modification of Smalian's equation and heartwood proportion derived from total log volume. The six relic logs studied at Site 2 could not be assessed for heartwood proportions, as the sapwood of these logs was largely absent owing to decay.

Log processing

Logs were processed at four different sawmills, each operated by a different sawyer. The six relic logs from Site 1 were sawn on a Wood Mizer LT70 band mill with a 0.32-cm (1/8-in.) kerf. The seven logs cut from standing but declining trees sawn at Site 2 were sawn using a Wood Mizer LT15 band mill with a 0.32-cm (1/8-in.) saw kerf. The two logs sawn from standing but declining timber harvested from Site 3 were sawn using a Wood Mizer LT40 band mill with a 0.32-cm (1/8-in.) kerf. The nine logs cut from Site 4 standing-declining trees were sawn using a Select Sawmill (band mill) with a 0.48-cm (3/16-in.) kerf. In all cases, the sawyers were given full latitude to saw each log as they normally would to produce the highest-value products using their standard appraisal and sawing strategies.

Given the variability of the sites, sawmills and operators, log sizes, and log conditions (relic vs. standing trees) and the small sample sizes examined, this study cannot be regarded as a rigorous examination of koa recovery. Rather, it provides initial recovery and quality benchmarks for sawmillers, forest landowners and managers, and scientists studying koa regeneration and silviculture.

Lumber measurements

Lumber size, defect pictures and measurements, and heartwood proportions.—Every board sawn from each study log was immediately labeled with a log number–board number combination code to maintain unique identity that allowed tracking back to the original log. Labels were applied consistently so that the orientation of the board ends relative to the large and small ends of the logs could be tracked. During sawing, one team member charted the order and orientation of each board sawn out of the log, giving us the ability to relate lumber defects to log defects.

Detailed lumber data were collected that were similar to those collected on the logs: board length, width, and thickness and defect types, sizes, and locations. The defect data collected included five parameters: (1) defect type, (2) distance from board end to the center point of the length of the defect, (3) distance from the top edge of the board to the center point of the width of the defect, (4) total defect length, and (5) total defect width. In addition, secondary or tertiary defect types, if present, were recorded (e.g., a decayed area that also included insect holes). Heartwood areas were measured and located using the same approach as used for defects. Only one face—the face away from the pith—of each board was evaluated.

Lumber grading procedures and defect area summaries.—Boards were graded using the computer program UGRS (Moody et al. 1998). This program has been used with success in multiple hardwood lumber research studies over the past two decades (e.g., Kline et al. 2001, Boden et al. 2005, Bond and Wiedenbeck 2006). The UGRS program grades boards into six National Hardwood Lumber Association (NHLA 2014) grades: FAS, FAS-1F, Selects, No. 1 Common, No. 2A Common, and No. 3A Common. It does not have the capacity to distinguish No. 2B or No. 3B Common grades.

Grading rules were modified to reflect how koa lumber is marketed. Lumber was graded using two modified grade rule sets:

1. Modified hardwood grade rules in which various size and cutting limitations in the standard hardwood grade rules (NHLA 2014) are modified to reflect practice in koa processing.
2. Modified hardwood grade rules as in No. 1 except areas of sapwood treated as defects.

The first set of modified grading rules made changes to the dimensions (length and width) and clear-cutting limitations as follows:

- The minimum allowable rough widths of boards for the three highest grades (FAS, FAS-1F, and Selects) were reduced from 15.2 cm (6 in.) to 7.6 cm (3 in.) for FAS and FAS-1F and from 10.1 cm (4 in.) to 7.6 cm (3 in.) for Selects.
- The minimum allowable rough lengths of boards for the three highest grades were reduced from 2.4 m (8 ft) to 1.2 m (4 ft) for FAS and FAS-1F and from 1.8 m (6 ft) to 1.2 m (4 ft) for Selects.

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- Minimum lengths and widths of clear face cuttings were reduced for all grades to 30.5 cm (12 in.) long by 7.6 cm (3 in.) wide.
- The maximum number of cuttings allowed to meet the required clear-area requirements for each grade was increased from one to two for the three smallest categories of cutting sizes.
- The minimum clear-face surface measure considered for each of these size categories was reduced to two (i.e., an area 0.6 m [2 ft] by 30 cm [12 in.] or its equivalent—288 in^2) from four and three for Selects and Better and No. 1 Common, respectively.

The second set of modified grading rules treated sapwood portions as defects because heartwood is the portion of the board that is desired and sapwood is of very low value. Sapwood is often removed from a piece of lumber during processing.

These modifications, in effect, reduce many of the size requirements for the higher lumber grades but maintain the clear-area percent required for boards to meet the various grades (NHLA 2014): FAS, 83.3 percent; FAS-1F, 83.3 percent; Selects, 83.3 percent; No. 1 Common, 66.7 percent; No. 2A Common, 50 percent; and No. 3A Common, 33.3 percent.

To supplement the lumber grade information in describing the quality of the koa lumber recovered, defect counts and area summaries were compiled for different defect types by lumber grade and sample site.

Basic descriptive statistics and comparisons

Regression analysis was used to test for relationships between heartwood proportions and log small- and large-end diameters. Analysis included both small- and large-end diameters as predictor variables as well as the cross between the two variables. The relationships between the volume-based lumber grade proportions recovered from logs and small- and large-end log diameters were also examined using regression analysis.

Analysis of variance (ANOVA) tests were used to test volume-based lumber grade recovery differences between standing dead and dying logs and relic logs. Both the No. 1 Common & Better (No. 1 Com. & Btr.) and the No. 3A Common & Worse (No. 3A Com. & Wrs.) proportions were tested.

SAS Enterprise Guide 6.1 (SAS Institute Inc. 2013) was used to conduct linear regression and ANOVA tests. Tests were conducted using a statistical significance criteria of $P = 0.05$. It was especially important to check for violations of the assumptions associated with conducting these statistical tests owing to the very small sample sizes. Because regression and ANOVA tests assume that the variances of populations from which samples are drawn are equal, both Levene and Bartlett tests for variance equality were conducted on all tested samples.

Results and Discussion

Throughout this section, two important distinctions are relevant and cited: (1) Site 1 logs are logs that were already on the ground for an unknown length of time (more than a year), and (2) Site 3 averages are based on only two logs, so these results are not meaningful by themselves. In some cases, Site 3 numbers are not included in the presentation of site-based results. It is noted when these data are excluded.

Cubic foot recovery

Volume recovery and comparison between standing dead and dying and relic log recoveries.—Recovery is based on the nominal dimensions (e.g., 1 in. thick by 6 in. wide by standard length in inches) of green (i.e., not air-dried or kiln dried), rough (not surfaced) lumber. Both gross lumber recovery (ft^3 lumber/gross ft^3 log volume $\times$ 100) and net lumber recovery (ft^3 lumber/net ft^3 log volume $\times$ 100) were calculated. Mean gross green recovery from all sites ranged from 18 to 90 percent with a mean of 71 percent (Table 2; Fig. 3). The mean gross lumber recovery percent for the six relic logs (69.9%) is about equal to the mean for all 18 logs from standing dead and dying koa trees (71.4%), although there is substantial variation in gross recovery among the standing dead and dying sites.

Recovery is typically based on net log volumes—after deductions have been made for defects that reduce the log's useful volume. The mean net lumber recovery for the 24 old-growth koa logs was 89 percent. Comparing the two types of logs evaluated in this study, the mean net recovery for the 18 logs from standing dead and dying old-growth trees was 89 percent, while the mean rate for the six relic logs (Site 1) was similar (90%). The standard deviation of the recovery rates was substantially higher for the 6 relic logs than for the 18 logs from standing trees (Table 2). Higher variability in recovery of relic logs can be attributed to two factors. First, these logs were more difficult to scale (i.e., estimate the amount of defect to deduct), as they had lost most of their bark and sapwood and contained significant seasoning defects, such as checks, splits, and shake, and the wood appeared darker due to weathering. Second, these logs had more inherent variability in their potential lumber yield due to log differences attributable to the varied lengths of time they were on the ground (Fig. 2).

Recoveries by log size for logs from standing dead and dying and relic old-growth koa.—Recovery is often influenced by log diameter. Larger logs may be sawn into wider and thicker lumber, and volume losses related to saw kerf should be less than for smaller-diameter logs. Larger-diameter logs also offer more options for producing different sizes of lumber to maximize recovery. Regression analysis of volume recoveries by log small-end diameter indicated lack of significance for both gross and net recoveries.

Log surface defects.—Face defects that are visible on the sides, or faces, of the logs give indications of internal log defect occurrence and severity. Differences in the occurrence rates of different types of face defects were discovered among sites. The relic logs (Site 1) had a significantly higher proportion of decay-type defects than was found at the other sites—64 percent of total log defect area (Table 3). In contrast, Site 2 logs had a notably higher proportion of split-type defects compared with the other sites. In particular, Site 2 logs had more and larger seams (open or callused over longitudinal separation of bark and wood fiber) than did the logs sampled at the other locations. Rise-type defects, bumps in particular, were more significant at Site 4, making up 22 percent of total log defect area at that site (Table 3). Related to this is the branch-type defect occurrence rate at Site 4, making up 30 percent of log defect area. Rise-type defects usually occur in association with and proximal to branches. The exceptionally low rate of occurrence of injury-type defects on logs from Site 1 may

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Table 2.—Green lumber volume recovery from Acacia koa *logs harvested and sawn at four locations on the island of Hawaii.*[a]

Log source	Log type	No. of logs	Mean (SD) gross recovery (%)[b]	Mean (SD) net recovery (%)[b]
Site 1	Relic	6	69.9 (29.1)	89.7 (39.7)
Site 2	Dead and dying trees	7	65.8 (14.0)	87.8 (13.4)
Site 3	Dead and dying trees	2	66.6 (0.6)	86.6 (14.9)
Site 4	Dead and dying trees	9	76.8 (3.5)	90.9 (23.3)
All logs from dead and dying trees		18	71.4 (10.3)	89.3 (18.3)
All logs—dead and dying and relic		24	71.0 (16.2)	89.4 (24.3)

[a] Log volumes were calculated using the Patterson and Doruska (2004) modification to Smalian's equation.

[b] Gross recovery = ft^3 lumber ÷ total log volume before scale (defect) deductions; net recovery = ft^3 lumber ÷ net ft^3 logs; these percentages are sometimes referred to as the "lumber recovery ratio."

indicate that these logs were not butt logs but rather were cut from higher up on the tree bole.

Heartwood proportions by site and log diameter.—The value in koa is in the darker-colored heartwood, not the light-colored sapwood. Therefore, having higher percentages of heartwood in the trees and logs is a factor in prices paid for koa stumpage and logs. Heartwood color and figure (curl) are attributes on which koa restoration and genetics research programs are focused. The heartwood–sapwood fraction measurements taken on logs from the standing dead and dying old-growth koa trees indicate a mean heartwood proportion of just over 86 percent (Table 4). The mean heartwood proportions at Sites 2 and 4, the two sites at which larger numbers of logs were sampled, were slightly lower and slightly higher than the overall mean, respectively. At each of these two sites, logs with heartwood amounts under 80 percent were observed. At Site 3, where we had the opportunity to sample only two logs, the heartwood proportion was over 90 percent. Table 4 and this discussion do not present results for log heartwood amounts for the relic logs because residency time of these logs on the ground, in all cases, was long enough to cause complete deterioration of the sapwood.

The test of the linear relationship between log large-end diameter and heartwood proportion for the 18 logs sampled from standing dead and dying old-growth koa trees was not significant ($R^2 = 0.15$; $P = 0.1135$). Indication of a relationship between small-end diameter and heartwood proportion for these same logs was even weaker ($R^2 = 0.08$; $P = 0.2524$; Fig. 4). The two sets of points circled are for two outlier logs—one a very small-diameter, upper log with heartwood making up 92 percent of the cross-sectional area on the log ends and the other a large-diameter log with only an average amount of heartwood. The model with both small- and large-end diameters entered as main effects along with the interaction term (SED × LED) was not significant ($P = 0.2233$).

The possibility that the non–butt logs included in this analysis might distort the regression results led to regression analysis being repeated for the 14 butt logs. The alternate regression analyses were, as before, not significant. These log diameter–heartwood proportion results are from a small sample, 18 logs, all considered old-growth logs (>50 yr old). It would be informative to have a more precise knowledge of the age of these logs, but as a tropical hardwood with indistinct growth rings, koa age cannot be determined by increment cores.

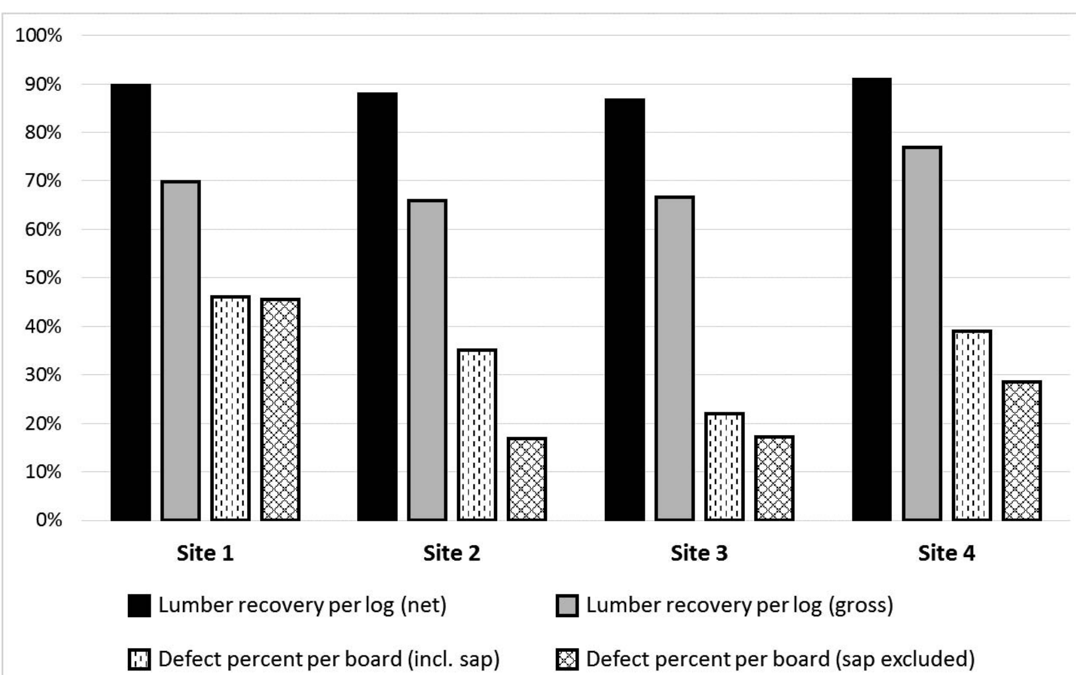

Figure 3.—Comparison of average cubic volume recoveries per log and defect proportions per board by site.

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Table 3.—Total area of log defects and defect occurrence rates by defect type and sampling site.

Defect type	Site no. (no. of logs) 1 (6 logs)[a]	2 (7 logs)	3 (2 logs)	4 (9 logs)	All sites (24 logs)
Branch-type defects (branch, crotch, overgrown knot, adventitious cluster, heavy/medium/light distortions, double pith) (in^2)	1,430	514	494	4,264	6,702
Percentage of total defect area at site	10	6	46	30	18
Percentage of all defects at site	20	17	31	39	28
Decay-type defects (heart rot, decay, incipient decay, bark pocket) (in^2)	9,032	1,333	473	1,565	12,403
Percentage of total defect area at site	64.0	16.0	43.8	11.0	33.0
Percentage of all defects at site	26	23	28	16	21
Split-type defects (split, check, heart check, ring shake, crack, seam) (in^2)	2,699	4,572	78	3,510	10,859
Percentage of total defect area at site	19	54	7	25	29
Percentage of all defects at site	37	44	14	30	33
Hole-type defects (large, medium, small holes) (in^2)	204.00	15.95	18.75	127.00	366.00
Percentage of total defect area at site	1	0	2	1	1
Percentage of all defects at site	8	6	10	3	6
Injury-type defects (mechanical damage, wound, cat face) (in^2)	180	1,046	5	1,524	2,755
Percentage of total defect area at site	1	12	0	11	7
Percentage of all defects at site	2	6	10	6	5
Rise-type defects (bump, bulge, surface rise) (in^2)	660	947	10	3,100	4,717
Percentage of total defect area at site	5	11	1	22	12
Percentage of all defects at site	5	4	7	6	6
Total area for all defects (in^2)	14,205	8,428	1,078	14,088	37,801
Total no. of all defects at site	92	70	29	144	335

[a] Site 1 logs were relic logs cut out of trees that had fallen to the ground at an unknown time (years) before being brought to the sawmill. Site 1 defects included two logs with sweep defects that are not shown in this table because a defect area was not associated with the sweep. Count-based percentages do not add to 100% for Site 1 and for the summary column because of this noninclusion.

Information available in the literature about the relative proportions of heartwood and sapwood is scant. Data presented in the literature have remarked that koa sapwood in mature trees is typically about 1 inch in diameter and almost never more than 2 inches, and younger koa trees may have greater amounts of sapwood (Skolmen 1974, Loudat and Kanter 1996). The only study results available on koa heartwood amounts concerned the development of heartwood in young (10- to 20-yr-old) *A. koa*. Examination of 20 young koa trees suggested that koa heartwood is absent in 10-year-old trees but present in dominant and codominant 15- and 20-year-old trees (Dudley and Yamasaki 2000).

Heartwood proportions in lumber.—The sapwood amount left on the outermost boards sawn from a log might be edged off in normal operations, but for this study, the board defects were evaluated as the boards came off the breakdown saw, so differences in sapwood amounts between sites should be only minimally, if at all, attributable to processing differences.

Ultimately, the amount of heartwood recovered in the lumber sawn from koa logs is what impacts the profitability of koa harvest and sawing for the small-scale logging and sawmill operations that produce the koa lumber for the marketplace. The darker color of the heartwood portion is what most lumber buyers demand. The heartwood areas for each board measured during the defect evaluation stage of data collection also are summarized in Table 4. Similar to the results of the examination of heartwood proportions in logs, Site 1 boards had the highest heartwood content with Sites 3, 4, and 2 having successively lower average amounts of heartwood. The mean heartwood proportion measured for the 463 boards was 89 percent, and 48 percent of all boards contained no sapwood (Table 4).

Table 4.—Koa log heartwood proportions based on heartwood and sapwood areas measured on the large and small ends of each log (proportions are a simple average of the two end measurements) and heartwood content of lumber sawn from these logs by study site.

Site	Log type	Logs: Mean (SD) heartwood proportion (%)	n	Range (%)	Lumber: Mean (SD) heartwood proportion (%)	n	Proportion of boards with no sap (%)
Site 1: west side; 4,900 ft	Relic	DnM[a]	6	DnM	99.3 (2.8)	126	89.7
Site 2: east side; 6,000 ft	Dead and dying	83.6 (4.1)	7	75.7–88.3	82.1 (21.7)	153	38.6
Site 3: east side; 4,400 ft	Dead and dying	90.3 (2.1)	2	88.9–91.8	94.3 (13.1)	27	70.4
Site 4: west side; 3,500 ft	Dead and dying	87.5 (6.7)	9	74.2–93.4	90.7 (14.3)	283	50.5
All logs from standing dead and dying trees		86.3 (5.8)	18	74.2–93.4	89.0 (17.5)	463	47.7

[a] DnM = did not measure. Because of the length of time these relic logs had been on the ground, sapwood discoloration and losses due to sapwood decay made heartwood–sapwood assessments infeasible.

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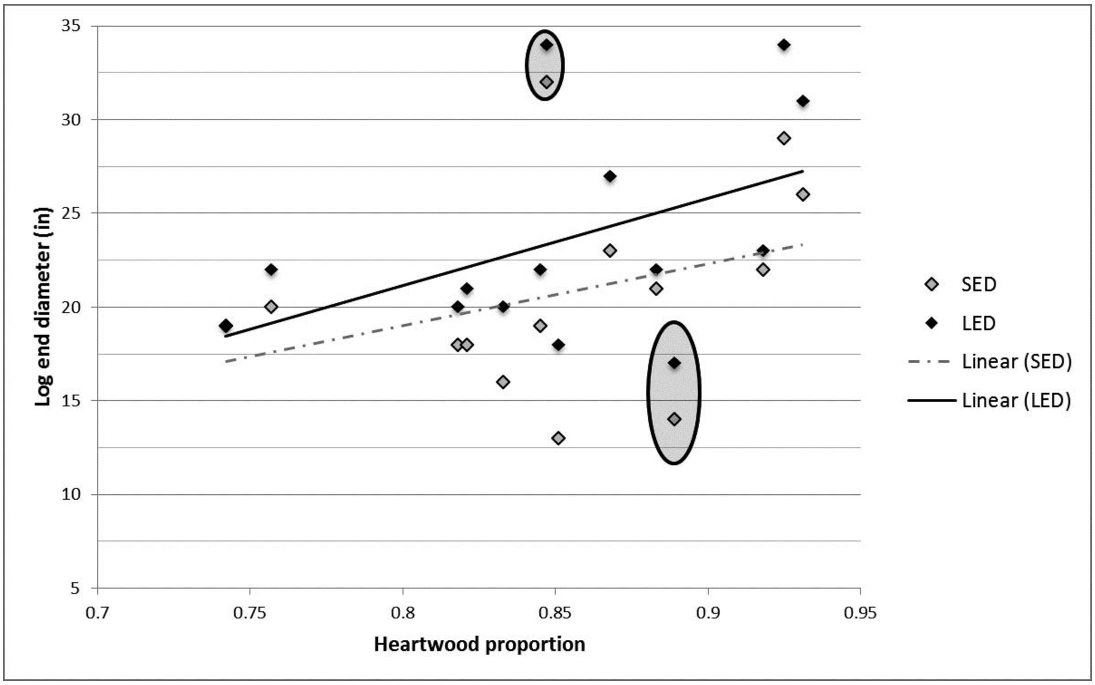

Figure 4.—Scatterplot of log end diameters compared to the average heartwood percentage measured for each log. SED = small-end diameter; LED = large-end diameter.

Lumber grades based on two different sets of grading standards.—The grades recovered from the 24 koa logs are categorized using the grade terminology set forth in the NHLA (2014) grade rules, with the three highest grades—FAS, FAS 1-Face, and Selects—grouped together as Selects & Btr. We have taken the liberty of extending the definition of high-grade lumber to include No. 1 Common (thus, No. 1 Com. & Btr.) in parts of the analyses and discussion. Similarly, lower-grade lumber is sometimes grouped together as No. 3A Common & Worse (No. 3A Com. & Wrs.)—a group that includes No. 3A Common and Below Grade boards.

Since Rule Set 2 provides the closest approximation to value assignment by the small-scale manufacturers and buyers of koa, the count-based and volume-based percentages for each grade based on this rule set are the focus of Figure 5. For all 24 logs (3 FS log Grade 1, 7 FS log Grade 2, and 14 FS log Grade 3), the percentage of the sawn boards that graded No. 1 Com. & Btr. using the ''koa rules with sapwood considered a defect'' (Rule Set 2) was 42 percent (Fig. 5). Using the same grading criteria, the volume-based percentage of the recovered lumber that was No. 1 Com. & Btr. was 53 percent (Fig. 5). Based on these percentages, it is evident that larger koa boards tended to be higher in grade than smaller boards.

Grading the lumber using Rule Set 1, in which sapwood is not treated as a defect, resulted in 54 percent of the boards and 65 percent of the board volume being No. 1 Com. & Btr. The 12-percentage-point difference in the high-grade lumber recovery results between the two grading protocols is considerably less than it would be for many hardwood species. This difference represents the lost value associated with strong market preference for heartwood color in koa products.

Lumber grade recovery for logs from standing trees versus relic logs.—The amount of defective area and grade distribution of the lumber sawn from the koa logs that were removed from standing dead and dying trees was generally of higher quality than the lumber recovered from the downed, relic logs (Fig. 3). The proportion of the standing dead and dying trees that graded (using Grade Rule Set 2) as Selects & Btr. and No. 1 Common was substantially higher than for the relic logs (Fig. 5). This was true for proportions based on board volumes and on board counts. Given that the sapwood amounts in the logs from relic trees were almost nonexistent, using Grade Rule Set 2, in which sapwood is treated as a defect, would negatively impact the grade recoveries of the nonrelic logs more than the relic logs. The high proportions of No. 3A Com. & Wrs. lumber derived from relic logs (Fig. 5) support the deduction that the sawing of relic logs produces lower-grade, lower-quality lumber than the sawing of standing dead and dying old-growth trees.

The results of both the Levene and the Bartlett tests indicated that the homogeneity of variance assumption for the use of the ANOVA procedure to compare No. 1 Com. & Btr. proportions derived from standing old-growth versus relic logs was reasonable (Levene, $P = 0.3289$; Bartlett, $P = 0.6323$). The ANOVA results indicated a significant difference in high-grade lumber recoveries between the two sources of logs ($P = 0.0160$). The same was true for the ANOVA results comparing the No. 3A Com. & Wrs. (the lowest-grade group). Real and substantial differences exist in the quality of lumber that can be recovered from old-growth koa trees that are still standing, even those that are dead, compared with those that have fallen and are harvested off the ground as relics.

Lumber volume–based grade recoveries by log size.—Examination of lumber volume recovery percentages in the different lumber grades in relation to log small-end (scaling) diameters did not point to a log diameter–lumber grade distribution relationship for this set of koa logs. For the nonrelic, old-growth koa logs, the difference between the

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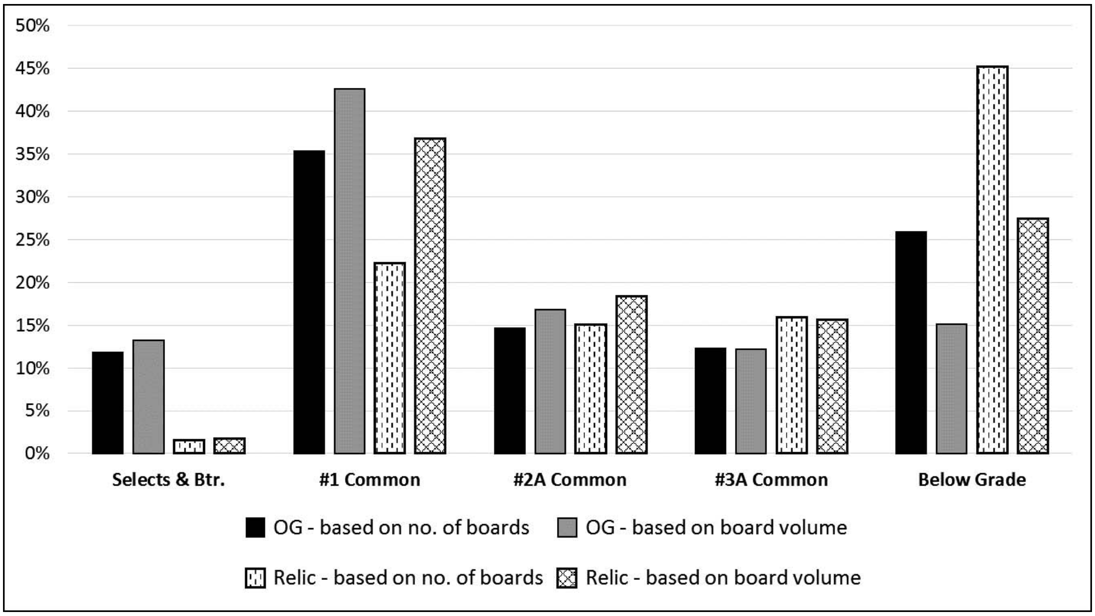

Figure 5.—Lumber grade distribution comparisons, based on both board counts and volumes, between logs from 18 standing old-growth (OG) trees and 6 fallen or relic trees. Grades based on lumber grading Rule Set No. 2, in which size and cutting limitations in the standard hardwood grade rules (National Hardwood Lumber Association) are modified to reflect practice in koa processing and areas of sapwood are treated as defects.

percentage-based volume yield of No. 1 Com. & Btr. lumber (the highest-grade group) and the No. 3A Com. & Wrs. (No. 3AC and Wrs.; the lowest-grade group) lumber yield averaged 27 percent. Of the 18 logs in this group, 12 produced a higher volume of No. 1 Com. & Btr. lumber than No. 3A Com. & Wrs.

The dispersion of grade recoveries compared with log diameters is shown in Figure 6. Examination of the relationship between SED and No. 1 Com. & Btr. recovery using regression analysis indicated the lack of linear relationship ($P = 0.3613$). A regression test also was conducted to examine if there was a linear relationship

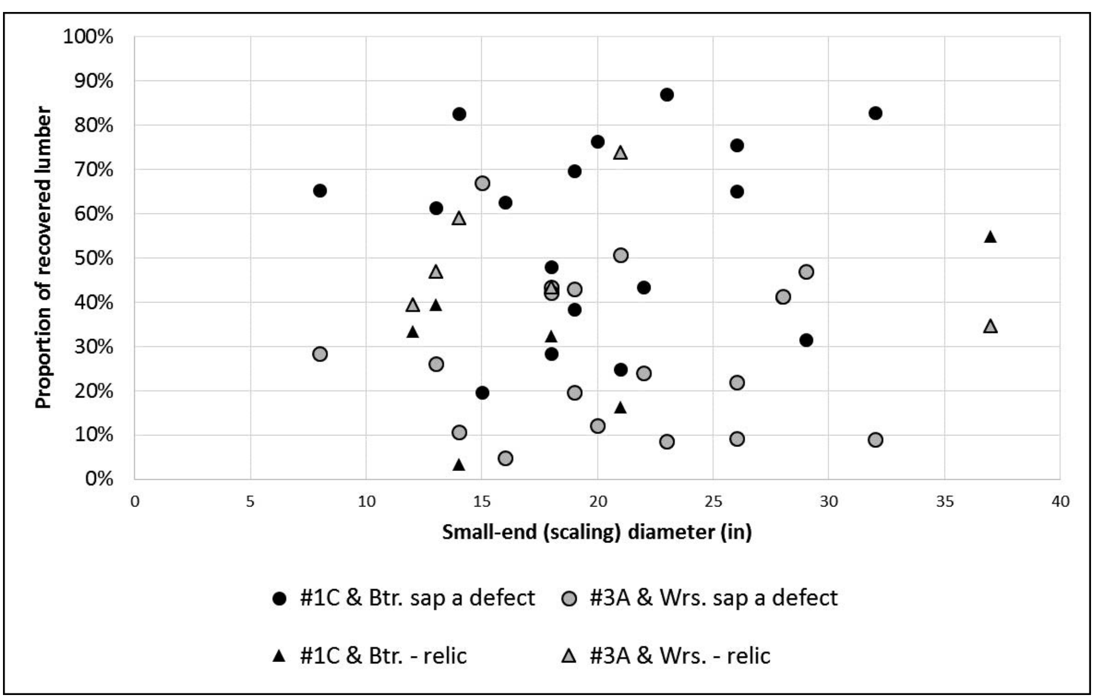

Figure 6.—Yields of the highest-quality (No. 1 Com. & Btr.) and lowest-quality (No. 3A Com. & Wrs.) lumber grade groups based on lumber volumes by small-end log diameter (scaling diameter). Grades based on lumber grading Rule Set No. 2, in which size and cutting limitations in the standard hardwood grade rules (National Hardwood Lumber Association) are modified to reflect practice in koa processing and areas of sapwood are treated as defects.

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between SED and No. 3A Com. & Wrs. recovery. This regression also was not significant. These results suggest that smaller-diameter koa logs may produce a mix of lumber grades that is relatively similar to that produced by larger-diameter logs. This result is not what is typically seen with other hardwood species. While lumber grades may be similar, the older trees may contain characteristics such as deeper color and/or desirable grain figure that make them more valuable on a board-foot basis.

Summary and Conclusions

Current practices require harvest of only dead and dying koa trees or using already downed material in wood products manufacturing. Significant amounts of rot are found in a large proportion of the standing dead and dying trees, but external defect indicators are absent (Baker et al. 2009). Downed material (relics) that were rejected and left on-site during previous harvests are now being collected and processed by some landowners and managers. Anecdotal reports indicate that the abundance of larger trees of higher quality in previous harvesting cycles was such that today's relics were considered low-value logs previously. Log scaling, defect estimation, and lumber recovery and grade predictions have not been fully developed and implemented for *A. koa* because of the highly variable nature of trees and logs. Also, because the value of koa wood is highly dependent on the color of the heartwood and whether curly figure is present, these potentially have a larger influence on the value of koa stems than do grade and volume of lumber recovered in sawing.

In this study, log and lumber data were collected at four locations on the island of Hawaii (Fig. 1) based on recommendations of local agency representatives and addressed site differences and origin. Six relic logs and 18 old-growth logs obtained from standing dead or dying trees made up the sample. Extensive data were collected for each of the 24 study logs to allow for correlations to be made among different koa log quality attributes and defects. This included heartwood measurements on both the small and the large ends because koa heartwood (and its color) are valued for high-end product manufacture.

Logs were processed at four different sawmills with each mill operated by a different sawyer. Boards were graded using the computer program UGRS (Moody et al. 1998) and grading rules modified to reflect how koa lumber is marketed. To supplement the lumber grade information in describing the quality of the koa lumber recovered, defect counts and area summaries were calculated for each board and then compiled by log and evaluated.

The mean net lumber recovery for the 24 old-growth koa logs was 89 percent. While volume recoveries were comparable between log types (89% for standing dead and dying logs and 90% for relic logs), the lumber recovered from the relic logs was overall of poorer quality. The relic logs produced lumber that had, on average, almost 45 percent defect. By contrast, the proportion of board surface area occupied by defects for the koa from the other three sites was, on average, 23 percent. Differences in the occurrence rates of different types of face defects were discovered, with the relic logs sawn at Site 1 having a significantly higher proportion of decay-type defects than was found at the other sites—64 percent of total log defect area.

The proportion of heartwood in koa trees and logs is one of the most important factors affecting the prices paid for koa stumpage and logs. The heartwood–sapwood fraction measurements that were taken on the standing but declining old-growth koa trees indicate a mean heartwood fraction in the logs of just over 86 percent. No linear relationship was found between log diameter and heartwood proportion for the 18 logs sampled from standing old-growth koa trees. The mean heartwood proportion measured for the 463 boards was 89 percent; 48 percent of all boards contained no sapwood.

For all 24 logs, the percentage of the sawn boards that graded No. 1 Com. & Btr. using the ''koa rules with sapwood considered a defect'' (Rule Set 2) was 42 percent (Fig. 5). Using the same grading criteria, the volume-based percentage of the recovered lumber that was No. 1 Com. and Btr. was 53 percent. Grading the lumber using Rule Set 1, in which sapwood is not treated as a defect, resulted in 54 percent of the boards and 65 percent of the board volume being No. 1 Com. & Btr.

The proportional recovery of No. 1 Com. & Btr. lumber grades from logs sawn from the standing dead and dying koa versus logs from relic logs indicated a significant difference in high-grade lumber recoveries between the two sources of logs. Likewise, the proportion of No. 3A Com. & Wrs. lumber indicated that real and substantial differences exist in the quality of the lumber that can be recovered from the standing dead and dying old-growth koa trees compared with those that were felled in the past and are currently harvested off the ground as relics.

Examination of lumber volume recovery percentages in the different lumber grades in relation to log small-end (scaling) diameters did not point to a log diameter–lumber grade distribution relationship for this set of koa logs.

While this set of sample logs can be considered to be a ''woods-run'' sample reasonably representative of the qualities and sizes of koa logs currently being harvested and sawn by Hawaii's small logging and sawmill operators, it was a small sample. A much larger-scale study would be required to estimate lumber grade distributions for different log grades with any degree of confidence. The variability of defect types and recoveries from the different sites and log types is large enough that koa stumpage–log buyers must have good koa appraisal skills to be successful koa producers. Relic logs can yield lumber volumes that are comparable to the volumes from standing dead and dying old-growth koa trees, but the quality of the recovered lumber is considerably lower when color and figure are excluded.

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