An Examination of the Feasibility of Using Time-of-Flight Based Non-Destructive Evaluation to Assess the Soundness of Standing *Acacia koa*

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ABSTRACT

Koa (Acacia koa) trees are native to the islands of Hawaii but occur nowhere else in the world. It is the most important timber species for the manufacture of wood products in Hawaii and one of the most valuable species worldwide. Most koa trees harvested today are standing dead or are already on the ground (relic logs). Lumber recovery in milling koa is very low – about 20% of the koa log is recovered as lumber. Wounds, broken out limbs, and branch crotches provide visual indication of the likely existence of decay inside the koa tree, but the extent of this decay is highly variable and difficult to predict. The challenge for timber sellers and buyers is to form a reasonable estimation of the degree of decay and the volume of the log that is affected. One tool that has had some success in predicting wood quality, measures the time-of-flight (TOF) of stress waves and may offer insights into the trees' decay. The objective of this preliminary study was to evaluate the relationship between TOF stress-wave data and corresponding decay observations to determine the feasibility of using this technology on koa. TOF data was collected at three heights and in two directions per height on eight standing koa trees at a single harvest site on the Island of Hawaii. TOF data also was collected from the butt logs of these trees after felling. The variability in the TOF results was large among trees, ranging from 246 to 2092 meters per second. The correlation between tree TOF and butt log TOF and lumber recovery was high. The correlation between tree TOF and the visible decay area on the large end of the butt log also was significant. Tree TOF and small-end decay area for the butt log were not significantly correlated. The feasibility of using TOF to predict the value potential of the lumber sawn from the butt log of a koa tree is uncertain – while lumber volume recovery was correlated with TOF, the decay proportions of the lumber products recovered were not found to be correlated. The lack of correlation between TOF and lumber soundness may be the result of the technique used in mapping the quality characteristics of the lumber where only one side of each piece was diagrammed due to time constraints. To produce quality lumber from these logs, the sawing pattern may have excluded any decay areas, thus resulting in lower volume recovery, which was correlated with TOF.

1. INTRODUCTION

Koa wood (*Acacia koa*) is a culturally important and economically valuable hardwood species on the Hawaiian Islands. It is native to the islands of Hawaii occurring nowhere else in the World. It has been and continues to be an important timber species for the manufacture of wood products in Hawaii. Koa is one of the most valuable species in the World with prices typically ranging from $5 to $35 per board foot. It is used for a range of products from canoes to flooring to fine musical instruments. Because of the value of koa wood, understanding how log defects affect wood quality and value is critical. Much of what is being harvested today is dead, dying, and down wood (forest relics). While these trees/logs are being sought out and swept up with the expectation that high value wood with good color and figure will be recovered, the felling, bucking, and transporting of these massive logs can be dangerous, costly, and sometimes unproductive.

Research on non-destructive alternatives to assess mechanical and physical properties of wood and wood-based materials has been of interest for more than a decade (Pellerin and Ross 2002). Many studies have used technology based on the speed of sound to predict stiffness of softwood lumber or veneer (Ridoutt et al. 1999, Ross et al. 1997, Ross et al. 1999, Wang et al. 2004) and soundness (density) of hardwood trees and logs (Wang et al. 2005). Speed of sound also is referred to as acoustic speed, ultrasonic speed, or stress-wave speed (and

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sometimes the term speed is replaced with velocity). We used the Fakopp® tool (although there are others available) that uses the time-of-flight (TOF) method to measure acoustic velocity. TOF tools are designed to obtain acoustic velocity near the base of trees. Wang et al. (2007a, b) contains additional information on the relationships between tree and log acoustic velocity.

The rationale for testing this technology on koa is to determine if this inexpensive tool might help timber sellers and buyers to better predict the extent and severity of internal tree defects. Of particular interest for koa is the possibility of improving estimation of the extent and severity of decay. Wounds, broken out limbs (and/or rotten knots), and branch crotches provide visual indication of the likely existence of decay inside the koa tree. The challenge for timber sellers and buyers is to form a reasonable estimation of the degree of decay and the volume of the log that is affected. Another benefit that might be derived from being better able to estimate the soundness of standing koa trees relates to logging safety – old-growth koa with many massive limb, significant lean, and uncertain soundness is a challenge to fell safely. If largely unsound koa trees can be identified reliably before felling, the hazards associated with logging koa can be reduced. Our hope is that a TOF tool may offer insight that can improve koa management, valuation, and harvesting safety. If the results of our preliminary tests suggest that TOF might prove useful, more robust testing would be required. The objectives of this study were to investigate the potential viability of using a time-of-flight stress wave system to improve the prediction capabilities of foresters/producers in identifying the soundness of both standing koa trees and koa logs.

2. METHODOLOGY

Time-of-flight (TOF) data was collected on 10 standing koa trees at a single harvest site on the northeastern flank (windward side) of Mauna Kea on the island of Hawaii. Sample trees were not randomly selected as we were looking for certain defects common among old koa trees that presented a broad range of log quality in harvested trees. Silvicultural prescriptions by the landowner were in place for harvesting and our sample trees came from a small area (less than 2 hectares) designated for harvest. We selected trees that were widely dispersed within this area and were "typical" of the old-growth trees on this site. The logger, recognized as one of the more experienced on the Big Island (and who milled koa as well), answered questions and assisted in choosing a representative set of trees.

TOF measurements were conducted at three heights: 0.457m, 0.914m, and 1.372m above the ground. At each sampling height, two measurements were taken. These measurements were perpendicular to each other and oriented approximately north-south and east-west. For each of these measurements, a mean TOF was recorded which was based on three send-receive transducer observations. To calculate the TOF velocity for each measurement, tree diameters were obtained using calipers at each measurement location. Bark thickness also was measured. Significant, visible growth and defect characteristics that are known to be associated with decay also were noted for each tree.

After the sample trees were felled and skidded to the sawmill yard, the harvesting and milling crew bucked the logs. The logs were scaled by a forester who was an accomplished koa log scaler. Small- and large-end diameters (to 2.54mm) and decay percentages were measured for each log bucked from our sample trees. We remeasured the TOF's by locating paint marks previously placed on the trees that indicated the different measurement heights and the locations of the transducers around the circumference at each height. This provided us with TOF velocities from both the standing tree and the butt logs for comparison.

The lumber sawn from the butt logs of our sample trees was measured for volume and defect area. Defects were categorized by type and their locations and sizes were manually digitized in the sawmill's lumber yard. This data was subsequently entered into a database and analyzed using summary pivot tables. The digital data was used to calculate the decay component of each board. By combining the amount of decay amounts of each board derived from each log, the percentage of each log's total board volume comprised of decay was obtained. The volume and grade yields derived from the butt logs of each of our sample trees were used in the analysis.

For both the tree and log tests, the velocities measured at each sampling height were ranked from fastest to slowest. As stress waves move faster (at a greater velocity) through sound wood than through decayed wood, cross-sections that contain lesser amounts of decay should correspond to higher rankings.

With this data, Spearman's Rank Correlation analyses (non-parametric) of TOF velocities and log-end decay amounts, lumber volume recoveries, and lumber decay volumes were performed. These analyses were conducted using a 0.05 level of significance. The non-parametric analysis was used since the sample size was small and the variability among TOF measurements was significantly different for the three measurement heights. Since the sample sizes for these tests were small (n=7 or 8), the p-value for the Spearmen Rank Correlation Test was obtained from a table of critical values (McDonald 2009).

3. Results and Discussion

Figure 1 shows trees T8 and T10, the two judged to have the most unsound and sound wood, respectively, based on the TOF measurements. These pictures were taken of the worst side of each of these trees. The visual evidence captured in these pictures does not seem to indicate that tree T8 is significantly different (worse) than tree T10. They both have significant seams that extend well up the bottom log. We know that the butt log cut from tree T8 was highly decayed. In fact, the sawmill opted to not process it due to the amount of decay. The degree of decay in the butt log from sample tree T8 is evident in the picture series taken during log scaling (Figure 2). Pictures were taken as the logger bucked off successive 0.6-meter long sections in an attempt to reach wood sound enough to saw. Decay (heart rot) dominated the log's cross-section throughout.

Figure 1. Trees T8 and T10 would be judged, based on the TOF results shown in Table 1, to be the least and most sound, respectively, of the trees sampled on the Department of Hawaiian Homelands site off Mauna Road.

Table 1 provides the TOF results obtained from tests conducted on the sample of standing koa trees. Unfortunately, only 8 of the 10 trees sampled were able to be logged so we were unable to obtain TOF measurements on the logs and further quality assessments of the lumber from these two trees (T2 and T3); therefore, they were dropped from the table and the analysis.

Sample trees T8 and T10, although visually appearing very similar (Figures 1 and 2), turned out to be the lowest and highest quality trees, respectively, from among our eight-tree sample (Table 1) based on the TOF measurements taken on the standing trees. TOF results for the bottom log bucked from each of the remaining eight sample trees also are shown in Table 1, although the lowest sample location (height=0.457m) was not available for retest on trees T6 and T8 because it had been removed or comprised in the felling process. As in the tree TOF measurements, the TOF results for the measurements taken on the bottom log indicate that T8 has a significant wood density problem (i.e., high decay) and T10 has solid wood as indicated by a fast stress-wave velocity.

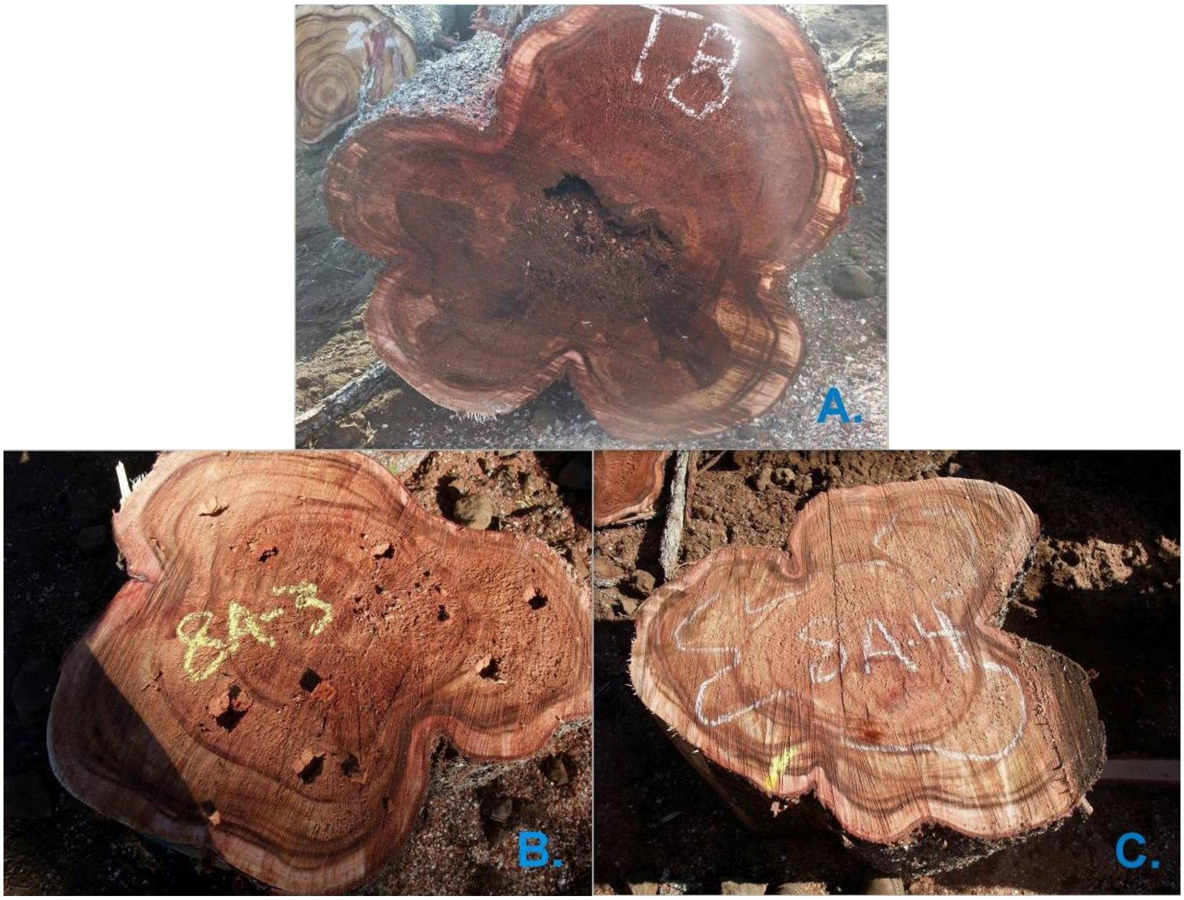

Figure 2. The large-end of the butt log bucked out of Tree T8 is shown in the top photograph A.; approximately 1.8 meters up this log the cross-section was still severely decayed and was easily pitted with a knife as shown in B.; 2.4 meters up this log decay was still evident – it is denoted by the white chalk marking the boundary of the heart rot C.

Overall, the fastest stress waves were recorded for trees T10 and T5 (Table 1). The slowest were recorded from trees T6 and T8 (Table 1). The decay/rot proportion measured on the large-end of the butt logs of these eight trees is in agreement with these stress wave velocity results for samples T10, T5, and T8, but not for T6. Since stress waves travel through sound wood faster than they do through unsound wood, the faster stress waves should be associated with the sample trees that have the higher sound wood percentage at the base of the butt log. Sample tree T6 is the anomaly based on this simple evaluation. The stress wave results for both the standing tree and the butt log of T6 indicate that the wood at the base of this tree was more unsound than for all but tree T8. However, the large-end decay percentage for the butt log sawn from this tree was 26% (Table 1) – an intermediate amount of rot as compared to the other seven samples. Based only on large-end decay/rot percentage, T7 should have recorded significantly slower stress wave velocities than T6.

Visual evidence of unsound wood on the ends of logs is widely used and generally trusted as a means of estimating log scale – the board foot volume that a given log is expected to yield based on its large- and small-end diameters, length, and the presence (or absence) of defects that will lead to reductions in lumber volume recovery. However, for the old-growth, large diameter koa that is being harvested today which has large branches, significant amounts of lean, sweep, and crook, and many seams running along the length of the logs, this visual assessment of log ends may not be as reliable as for others species and smaller diameter trees. With the ultimate goal of log scaling being to accurately predict the volume and (to some extent) the grade/value of lumber that may be recovered from a given log, we assessed the use of TOF as an indicator of log soundness not only by comparing it with log scale attributes, but also by comparison with the quantity and quality of the lumber recovered.

Table 1. Stress wave testing results from standing koa trees and corresponding logs from the Department of Hawaiian Homelands site on the east side of the island of Hawaii.

Tree number	Measurement height (above ground)	Tree dbh at measurement height	Time-of-flight (TOF) stress wave velocity				Decay proportion on large end of butt log
			Tree		Log		
	- - - - - m - - - - -		- - - m/s - - -	Rank* (1=best)	- - - m/s - - -	Rank* (1=best)	- - - % - - -
T1	0.457	0.516	361	7	495	6	34
	0.914	0.472	792	6	898	4	
	1.372	0.452	1,382	4	1,364	5	
T4	0.457	0.546	1,073	3	1,150	1[b]	10
	0.914	0.546	1,282	4	1081	2[b]	
	1.372	0.549	1,376	5	1,022	6	
T5	0.457	0.815	1,623	2[b]	975	2[b]	0[b]
	0.914	0.792	1,645	1[b]	444	6	
	1.372	0.813	1,579	3[b]	1,705	1[b]	
T6	0.457	0.798	630	6[a]	–**	–**	26
	0.914	0.676	585	7[a]	443	7[a]	
	1.372	0.640	890	7[a]	912	7[a]	
T7	0.457	0.699	673	5	524	5	73[a]
	0.914	0.635	792	5	450	5	
	1.372	0.612	1,720	2	1,491	4	
T8	0.457	0.818	246	8[a]	–**	–**	77[a]
	0.914	0.785	558	8[a]	395	8[a]	
	1.372	0.742	307	8[a]	372	8[a]	
T9	0.457	0.602	940	4	772	4	39
	0.914	0.528	1,331	3	1,049	3[b]	
	1.372	0.513	1,357	6	1,503	3[b]	
T10	0.457	0.518	2,092	1[b]	883	3[b]	0[b]
	0.914	0.508	1,608	2[b]	1,621	1[b]	
	1.372	0.513	1,797	1[b]	1,697	2[b]	

[a] trees with the slowest stress wave velocities
[b] trees with the fastest stress wave velocities
* for each measurement height
** measurement not available

Table 2. Summary of recovered lumber volume and decay content for all boards sawn from the eight-log koa sample.

Tree number	Decay volume in lumber	Rank (1=best)	Scribner overrun	Rank (1=best)
	- - - % - - -	- - - # - - -	- - - % - - -	- - - # - - -
T1	12	5	39	6
T4	11	4	77	2.5
T5	3	3	77	2.5
T6	<1.0	2	59	5
T7	15	6	74	4
T8	cull[1]	n/a[1]	cull[1]	8[1]
T9	28	7	1	7
T10	<0.5	1	164	1

[1] Log T8 was decayed throughout and was determined to be of no value (cull), therefore the volume recovered from this log was zero board foot and the decay content of boards was not available (n/a).

The volume of lumber recovered from the seven butt logs (bottom logs on measured trees) that were sawn during our study was measured and the Scribner scale-based overrun was calculated. Log T8 was culled for decay and not sawn as there was nothing of value that could be recovered (Figure 2). The overrun values for the seven logs ranged from 1% (Log T9) to 164% (Log T10, Table 2). The overrun percentages are in general agreement with expectations based on TOF values recorded on trees and logs and log-end decay amounts.

Table 3 shows the ranks for the six quality attributes assessed in this study. For each attribute, a rank of 1 is associated with the best wood quality result and a rank of 8 is associated with the poorest result. For example, log T8 received the rank of 8 for tree time-of-flight (Column A, Table 3) because the slowest ultrasound velocity was recorded for this log (slow velocity is associated with less sound wood). Log T10 received the rank of 1 for lumber recovery (Scribner-based, Column F, Table 3) because the best lumber recovery result was obtained for this log. In cases where the quality attribute measurements were the same for more than one tree/log, a mid-rank assignment was made (e.g., logs T4 and T5 have the same Scribner overrun in Table 2, both are given a rank of 2.5 in Table 3, Column F).

By comparing the wood quality ranks for a given log across columns in Table 3, it is possible to quickly identify those logs for which the TOF tool returned results that aligned with the quality measurements recorded for the log. Table 3 shows the ranks (1 to 8) of tree velocity (Column A), log velocity (Column B), where rank=1 indicates the fastest stress wave velocities. Column C displays the ranking of the logs' large-end (LE) decay percentage and Column D shows the rankings of the logs' small-end (SE) decay percentage. Column E ranks the logs in terms of their decay volume as proportion of total lumber volume sawn from each log, where rank=1 indicates the log with the smallest decay component. Column F ranks the logs based on their lumber volume recovery, where rank=1 indicates the highest lumber recovery. Finally, Column G presents the sum of the differences of ranks for each log as compared to the rank in Column A. However, the rank in Column G was calculated as the sum of the differences in rank for each of the quality attributes (Columns B to F) that we tracked as compared to the rank of the velocity of stress waves measured using the time-of-flight tool on the base section of the standing tree (Column A). The sum of these rank variances is given for all five attributes (Columns B, C, D, E, F), but only four attributes – excluding the small end decay percentage attribute (Column D) – were used to calculate the sum of rank differences (Column G). The four attribute-based sum of ranks (Columns B, C, E, and F) were used since the TOF tool is designed for use in evaluating the soundness of the wood cross-section at the height where the test is conducted (in this case, near the large end or base of the tree) but is not able to determine wood soundness at distant locations. Thus, Column D values are not expected to be correlated with Column A values.

Log T10's quality attributes appear to align well with the TOF results obtained on both the tree and the log – this tree and the butt log bucked from this tree had the fastest TOF velocity of the eight logs studied. This correlated well with Log T10's quality results as it had the highest recovery, the lowest volume of decay in the lumber sawn from the log, and the best (tied with Log T5) large-end decay result. The sum of rank differences for T10 (Column G, Table 3) indicates how well aligned the quality attributes are with the TOF result in Column A. Quality attributes for logs T8, T1, and T5 also align well with the relative TOF results for the tree (Column A). The sum of rank differences for logs T6 and T7 are the least well-aligned with their respective TOF results compared to the other trees in this sample. These are the two trees for which the use of the TOF tool to predict wood quality and value potential appears unreliable.

Table 3. Ranks of tree and log TOF velocities (Columns A and B) and tree quality attributes (Columns C to F) for the eight tress studied.

Tree number	A Tree velocity	B Log velocity	C LE decay percentage	D SE decay percentage	E Decay volume in lumber	F Recovery	G Sum of rank differences
	- - - - - - Rank (Difference to tree velocity, column A) - - - - -						
T1	6	6 (0)	4 (2)	1 (5)	5 (1)	6 (0)	3
T4	4	2.5 (1.5)	3 (1)	1 (3)	4 (0)	2.5 (2)	4.5
T5	2	2.5 (0.5)	1.5 (0.5)	1 (1.0)	3 (1)	2.5 (0.5)	2.5
T6	7	7 (0)	6 (1)	6.5 (0.5)	2 (5)	5 (2)	8
T7	3	5 (2)	7 (4)	6.5 (0.5)	6 (1)	4 (3)	10
T8	8	8 (0)	8 (0)	1 (7)	n/a[1]	8[1] (0)	0[1]
T9	5	4 (1)	5 (0)	8 (3)	7 (2)	7 (2)	5
T10	1	1 (0)	1.5 (0.5)	5 (4)	1 (0)	1 (0)	0.5

[1] Log T8 was decayed throughout and was determined to be of no value (cull), therefore the volume of lumber recovered from this log was 0 cubic meters and the decay content of boards was not available (n/a).

The results of Spearman's Rank Correlation Analysis indicate that the rank results for log TOF and tree TOF are highly significantly correlated ($0.001<P<0.005$). Also highly significant is the relationship between the ranks for lumber recovery and tree TOF ($0.005<P<0.01$). Large-end decay percentage results are significantly correlated with tree TOFs ($0.025<P<0.05$). Small-end decay percentage results and board decay percentages are not significantly correlated with tree TOFs ($P>0.10$). The results of Spearman's Rank Correlation Analysis comparing ranks for log TOF and the other log quality attributes yielded the exact same significance results as did the log TOF-based analyses.

The lack of a finding of significant correlation between the decay percentage on the small-end of the butt log and the TOF of the tree is not unexpected. Since the TOF measurement tool records the time between the initiation of a stress wave at a point around the circumference of a log and the first receipt of that signal at an opposite point in the same cross section, unsound wood sections distant from this cross-section are not detected by this tool and testing protocol. Thus, a correlation between the TOF velocity tests conducted at the base of the tree (near the large-end of the butt log) would only be correlated with the percentage of sound wood at the small-end of the butt log if there was a correlation between large-end and small-end decay amounts. This correlation was not significant for this study ($P>0.10$). Given the nature of the occurrence of decay in a tree, a weak correlation might be expected to exist between these quality attributes. We know that decay can originate from multiple sources, many of which impact the base of the tree more than upper sections, and that, over time, the decay may spread longitudinally. However, we would expect to detect this type of correlation only with a much larger sample of trees such that a more powerful statistical test could be conducted.

Had there been a significant Spearman's rank correlation between the percentage of lumber volume containing decay from each butt log and the TOF measurements conducted on the standing trees, the utility of this one-dimensional stress-wave based assessment system would have been much more promising for *Acacia koa*. Examining the ranks for the lumber decay volume attribute among the eight sample trees, it appears that there is only one tree for which this attribute aligns poorly with the standing tree TOF results – tree T6 (Table 3). While tree T6 had the next to worst rank for tree TOF (rank=7 out of 8), it had the second best lumber decay volume rank. For the attribute lumber decay volume, 50% of the variation in ranks between this attribute and tree TOF ranks was contributed by tree T6. The lack of agreement between the standing tree TOF for T6 and the lumber decay volume percent may be partially due to the fact that 0.61 meters were removed from the large end of the log before the log was loaded onto the sawmill for sawing. This was done because these bottom 0.61 meters were almost entirely unsound. Recall that our lowest TOF measurement was taken at 0.457 meters above the ground -- within that unsound log section. Another observation that may help explain the inconsistency between the rank for lumber decay proportion and standing tree TOF for log T6 is the distribution of lumber thicknesses recovered from log T6. The sawyer used in this study was looking to recover predominantly 29mm- and 54mm-thick lumber (referred to in the U.S. as $^{4}/_{4}$ and $^{8}/_{4}$ lumber). Of the seven logs sawn into lumber for this study, log T6 had the second highest proportion of lumber sawn to thicker dimensions (>54mm). The sawing diagram for this log shows that the decayed inner portions were sawn into thicker pieces, presumably because the value was so low due to the presence of decay that it was not worth spending time to saw thinner boards. Since we were only able to map the defect locations on one face of each piece of lumber recovered in sawing (due to time constraints) and we were mapping the "top" face (the face closest to the bark) on all boards to maintain consistency, the extent of decay inside these thick pieces was likely underestimated.

4. Summary and Conclusions

Using the Fakopp® tool which measures the TOF of stress waves traveling across the cross-section of a tree, may provide a non-destructive, early appraisal system for standing koa trees to evaluate the soundness of the bottom portion of the butt log. The rationale for testing this technology on koa is to determine if this inexpensive tool might help timber sellers and buyers better predict the extent and severity of decay. An associated benefit that might be derived from being better able to estimate the soundness of standing koa trees relates to logging safety – old-growth koa with many massive limbs, significant lean, and uncertain soundness is a challenge to fell safely.

Time-of-flight data was collected on 10 standing koa trees at a single harvest site on the island of Hawaii. TOF tests were conducted at three heights: 0.457m, 0.914m, and 1.372m above the ground. Eight of the sample trees were felled, bucked, evaluated, and sawn. Quality attributes that were assessed included the proportional decay amount visible on the large- and small-ends of the butt logs of the eight felled trees, the recovery (Scribner-based overrun) of the sawn trees, and the proportional decay occurrence on lumber sawn from each log. Before the logs were sawn, the butt log of each of the eight felled trees was assessed a second time with the TOF tool using the same sampling locations on the log as were used when assessing the standing trees.

Because the sample size was small (8 trees/butt logs), a non-parametric correlation test was used to test for significant relationships between the TOF variables and the quality attributes. The correlation between tree and log TOFs were highly significant. The strength of this relationship led to parallel results when correlation analyses were performed between tree TOF and then log TOF and the ranks of each of the four quality attributes measured in this study: Large-end decay proportion, small-end decay proportion, lumber volume recovery, and lumber decay proportion. Tree and log TOFs were both found to be significantly correlated with the proportion of decay on the large end of the butt log and with the lumber volume recovered in sawing. Neither tree, nor log TOFs were significantly correlated with the proportion of decay on the small end of the butt log or with the decay percentage present in the recovered lumber. The lack of significant correlation between TOF and lumber decay percentages was largely due to the influence of one tree/log (log T6). If this correlation had been significant, we could have concluded, with some degree of confidence, that the measurement of tree and log TOFs offered a viable method for assessing the quality potential of a koa stem before felling/sawing. While this correlation was not significant, a plausible explanation for the lack of significance relates to the abridged method of lumber diagramming that was used in order to keep up with the sawmill's rate of lumber production. In combination, the correlation analyses led us to conclude that there is a substantial opportunity for the time-of-flight assessment tool to provide helpful information on the soundness of standing trees such that an expanded study is warranted. An expanded study should involve selecting trees for TOF analysis from multiple harvest sites around the island of Hawaii and the tree sample at each site should be randomly selected.

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