Determining the Extent of damage in Snapped Southern Yellow Pine Trees with Acoustic Testing

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Abstract

Salvage of downed timber following a windstorm allows recovery of management options for landowners and wood products for industry. Because wood volumes are large and logging, transportation, mill storage, and processing capacities are limited, avoiding the selection of logs with damage can conserve those resources. Visual damage indicators are typically used to select and differentiate products, but damaged logs are still delivered to mills. Following experimental tree winching in 2021 and a tornado in 2023, we assessed lengths of broken trees with a Fakopp microsecond timer. Using a recognized defect limit (10% deviation from the maximum acoustic velocity) about 80 percent of volume in broken tops could be recovered. Standard rules of thumb applied from the end of visible damage resulted in the recovery of about 50 percent of the volume with a relatively low defect rate (<10%). Applying bucking rules developed from acoustic measurements based on distance from snap might be easier to apply and increase recovery rates to over 70 percent of broken top volume.

Tropical storms, tornados, and other severe winds are globally common, leading to risk of loss to timber resources (Dale et al. 2001, Ojha et al. 2020, Henderson et al. 2022, Cannon et al. 2023). Salvage harvesting of damaged timber following wind storms generates economic value (Prestemon and Holmes 2004) and provides landowners the opportunity to restore infrastructure (roads and firelines), prepare for forest regeneration, and mitigate risk of fire and pests (Clarke et al. 2023). Dead and damaged trees can be used for a variety of products depending on wood quality. While an instantaneous change to wood quality (fracture) occurs when stems are broken, dead stems begin to dry and suffer degradation shortly after storm events. In the southern United States trees killed by storms have little value for most solid wood products after about 4 months (Hamilton and Bardon 2011). Storm event characteristics as well as tree and landscape factors can influence the type and extent of tree damage (Suvanto et al. 2016, Rutledge et al. 2021, Fortuin et al. 2023). Merchandizing storm-damaged timber in a manner that minimizes cull logs before transport conserves resources (e.g., transportation, storage space, and mill capacity) following the event (Peralta et al. 1993). Logs for solid wood products are often transported long distances and then retained in wet storage for some time at the mill. Milling of logs with defects increases the investment in lumber likely to suffer a significant degrade (Aho and Cahill 1984). Rules of thumb for bucking and sorting sawlogs have been to cull 4 to 6 feet from the end of the visible split (Lupold 1996), but some have noted that 15 to 30 percent of logs salvaged and delivered to mills had damage that was retained after bucking (Alabama Forest Recovery Task Force 2008).

Nondestructive evaluation (NDE) of logs may yield some assessment of log quality before timber is loaded and delivered to mills. Time-of-flight measures from acoustic measurement devices have significant relationships with lumber quality and log (Butler et al. 2017) and tree (Rudnicki et al. 2017) quality measurements. Since

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time-of-flight measurements may identify tree defects (Schad et al. 1996), their use provides an opportunity to understand fracture location in broken stems beyond the visible split. Implementing NDE at production speed could improve the quality of logs that are salvaged (Carter et al. 2013, Walsh et al. 2014) in addition to the identification of storm-caused defects. The objective of this study was to use time-of-flight measurement to evaluate changes over increased distances from the broken end of saw-timber–sized stems. The relationships between measurements, tree size, damage characteristics and acoustic values might provide for refinement to bucking rules of thumb during salvage harvests.

Materials and Methods

We examined trees damaged following experimental tree winching in 2021 and tornado damage in 2023. We sampled longleaf pine (*Pinus palustris*) trees at The Jones Center at Ichauway (JC) that were snapped by applying static winching to measure tree stability (Cannon et al. 2015, Cannon et al 2024). Those trees were located near Albany, Georgia, and sampled in November 2021. The Oakmulgee (OM) trees were damaged by a tornado on January 12, 2023. The tornado damaged about 1,000 acres in the Oakmulgee Ranger District of the Talladega National Forest located west of Brent, Alabama. The sampled trees were in longleaf pine stands on the ridge tops and sampled in February and March 2023. A few JC snapped trees were dissected prior to November 2021 and some broken tops formed A-frames and were too high to reach from the ground. For the OM trees our goal was to sample 50 trees across a range of observed diameters at breast height (DBHs) and snap heights. In total we collected acoustic data on 30 JC longleaf pine trees, 38 OM longleaf pine trees, and 9 OM loblolly pine (*Pinus taeda*) trees.

We measured time-of-flight at several locations on each tree with a broken top. For each tree we located the last visible evidence of damage and took acoustic readings on the opposite face (Mahon et al. 2009) just distal to that point (Fig. 1). We measured stem diameter at each location with a caliper and estimated one-half of the stem circumference. The probes for the Fakopp microsecond timer were inserted into the sapwood of each tree at a 45° angle, pointed towards each other at opposite ends. Probes were set at a distance of one-half the circumference on two axes that ranged from 60° to 90° apart. Since many trees were on or near the ground, access to the bottom side of the tree was limited. We collected six readings for each of two axes at each location. The time-of-flight in microseconds (μs) was used to estimate the acoustic velocity in meters per second (m/s).

After the first reading, just past the end of visible damage, we advanced in 1-foot (30.5-cm) increments away from the defect or towards the tree top (distal) until the range (maximum–minimum) of all 12 readings was less than 10 percent of the mean. After that criterion was met, we collected an additional set of readings another foot distal from the snap. For the JC trees we took more sets of readings at a location every meter until 6 meter above the ground line. For the OM trees we took one more set of readings at a location 16 feet from the most distal location near the snap. We extracted one increment core to

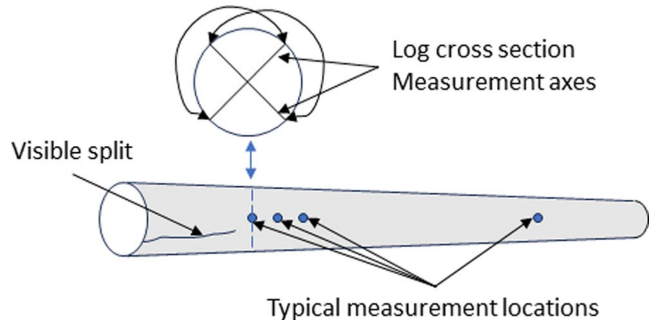

Figure 1.—Diagrams for measurement locations along the tree's length and a cross-sectional views of a typical sampling location.

determine dry density 4.5 feet (1.2 m) from the last acoustic measurement near the snap.

We used the criteria from (Wang et al. 2004) using the measured surface distance between the probes (about 0.5 × log circumference) instead of diameter to estimate the measured velocity time on per-length basis (T_m) and reference velocity (T_0) (Eq.). This approach was adopted to accurately capture the surface distance between probes. We estimated T_0 or reference velocity as the maximum of the mean velocities by sample location in each measured stem. The ratio is multiplied by 100 to yield the percentage of deviation from the reference velocity:

$$\Delta T = \left([T_m - T_0]T_0^{-1}\right)100$$

We estimated volume of the tree sections using the dimensions directly measured (DBH and total height) and a taper equation from Farrar (1987) with a Smalian formula. We estimated salvageable volume with bucking locations determined by the standard rules of thumb of 4, 5, and 6 feet from the visible crack (Lupold 1996), a threshold of ΔT of −10 percent, rules generated from a graphical analysis of the data, and rules from decision trees generated by Proc HPSPLIT (SAS Institute 2016). Decision tree options were grown—entropy and prune—cost complexity with leaves = 12. Trees were constructed for values of ΔT of −10 and −15 percent. We set training and validation datasets to equal 80 and 20 percent of the samples, respectively. Quality of salvaged logs was estimated by the volume weighted estimate of ΔT and the volume weighted mean of T_m.

Results

Since the goal was to evaluate salvage for higher-value products, the trees sampled had a minimum DBH of 8 inches with a 6-inch outside bark diameter top 16 feet from the snap (Table 1). There were relatively few large trees (>18-in DBH) in the sample areas and the large trees sampled tended to break near the ground or the base of the live crown (Fig. 2). There were trees with snap heights greater than those sampled but the outside bark diameters at 16 feet from the snap were less than 6 inches. The difference in tree number is due to the JC trees, which had dimensions measured but were not available for testing because they were destructively sampled prior to November 2021 or too high to reach.

Table 1.—Statistics for sample trees.

Variable	No. of trees	Percentile values			
		Mean	50th	10th	90th
DBH[a] (in)	87	14	14	10	18
Height (ft)	87	79	80	68	91
Height (ft) to 6-in top (OB)	87	59	61	44	73
Snap height (ft)	87	10	5	2	22
Dry density (g/cm^3)	74	0.55	0.53	0.43	0.64
Velocity (m/s)	77	2573	2582	2345	2856

[a] DBH = diameter at breast height; OB = Outside bark.

The results for ΔT versus distance from snap location across all trees are shown in Figure 3. At less than 5 feet from snap location, none of the mean values are within 10 percent of the reference velocity (T_0), indicating some defect. From 5 to 15 feet, values are generally between 5 and 10 percent of the reference velocity. At distances more than 15 feet from the snap location, the velocities were within 5 percent of the reference value. Most of the indicated defects would be excluded by removing 5 feet of log from the snap location.

Using ΔT of less than −10 percent as the indicator of defect, detectable defects were mostly in the first 4 feet from the snap for trees with DBH less than 14 inches (Fig. 4). For trees 14 to 17 inches in diameter at the snap location, some defects extended 10 to 15 feet from the snap location. On larger trees (DBH 18 in or greater) few defects were identified at more than 8 feet from the snap location. For trees with shorter sections above the snap (top wood), most of the defects were detected in the first 4 feet from the snap location (Fig. 5). For trees with more than 40 feet of top wood, defects extended farther from the snap location.

For the decision trees we applied variables that could be estimated by a loader or processor operator, which included diameter at the snap location in inches, the log length from snap location to a 6-inch top in feet, and the distance from the snap location in feet (Table 2). The misclassification rates were greater for ΔT of −10 versus −15. The model was better at identifying locations with solid wood and specificity was greater than 0.80 for all models. The classification indicated that defects were less likely when the salvageable top was shorter, either because it was a smaller tree or a higher snap height (Fig. 6). Decision trees indicate a bucking location of more than 14.2 feet from the snap would remove almost all defects. For longer tops stems could be bucked at 4.3 or 5.3 feet from the snap and the remaining stem sections would have from 64 to 80 percent defect-free measurements.

We compared volume recovery and volume weighted quality measures for (1) bucking at 4, 5, and 6 feet from

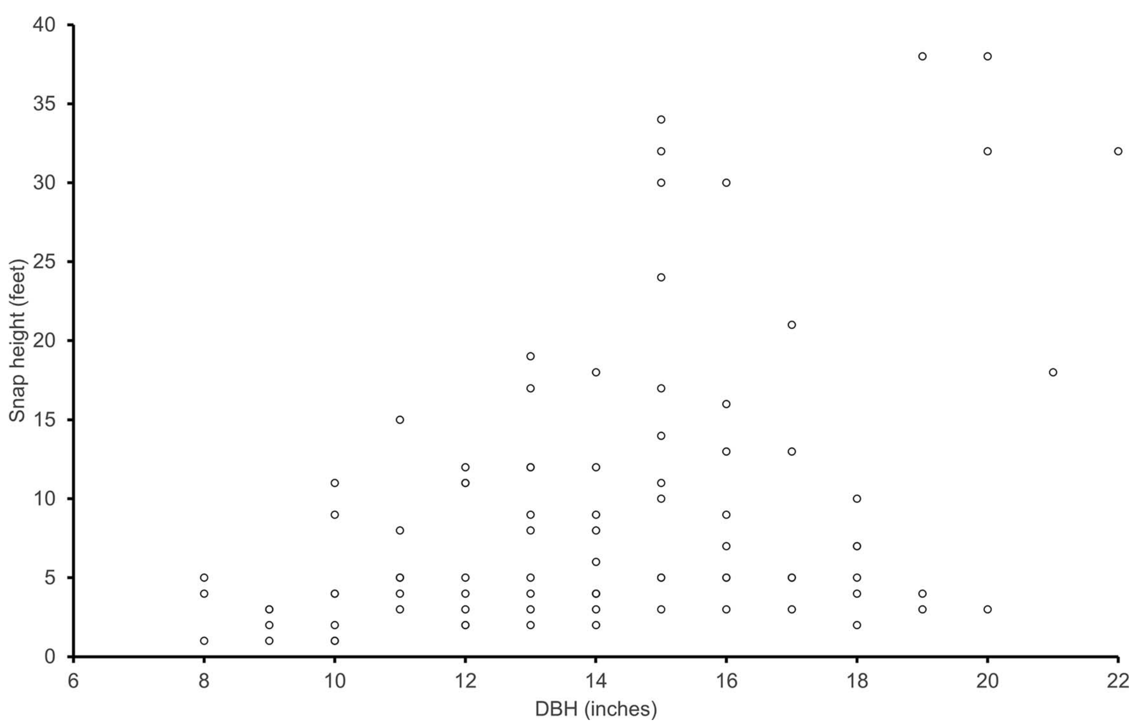

Figure 2.—Distribution of sample trees by tree diameter at breast height (DBH) and the snap height above the ground in feet.

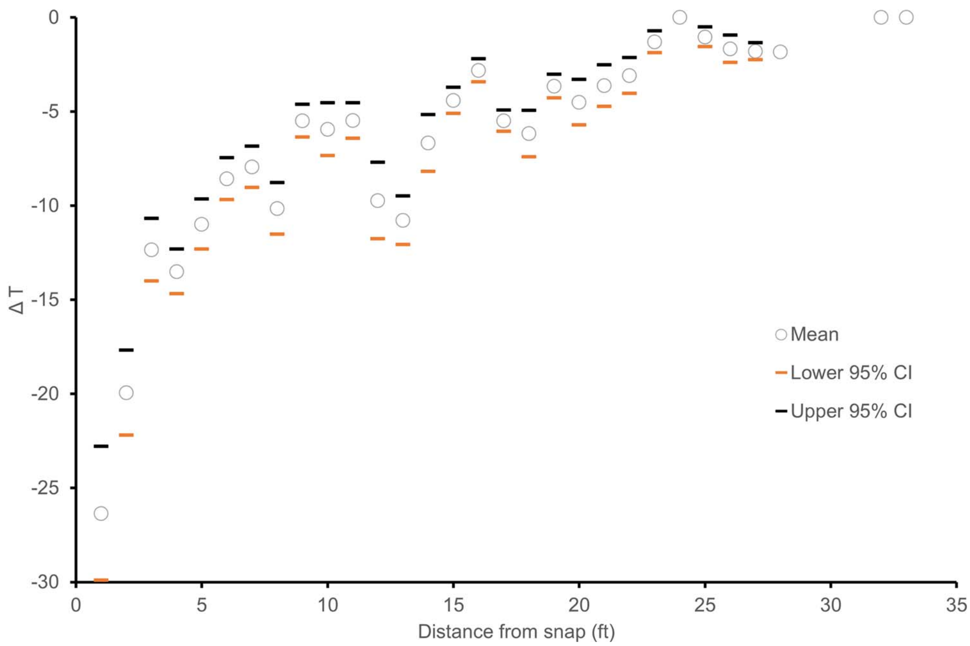

Figure 3.—Trend in mean deviation from reference velocity (ΔT) and the 95 percent confidence interval by distance from the snap location.

the end of the visible damage (V4, V5, and V6), (2) bucking when the value of ΔT was less than −10 (M10), (3) bucking using the decision tree rules at ΔT < −10 and < −15 (DT10 and DT15), and the application of the rules from graphical analysis in Figures 4 and 5 (GA10). For GA10, logs were bucked at 4 feet from snap when ≤12.5 inches in diameter at snap location and at 8 feet for trees >12.5 inches. The combined results from all the trees are in Table 3. The volume recovered compares the volume after bucking to the total volume above the snap location to a 6-inch top. Three bucking methods (M10, DT10, and DT15) recovered from 0.79 to 0.82 of total volume. Since logs were bucked when defects were indicated M10 had a misclassification ratio of 0. For DT10 and DT15 the bucking results included tree sections with defects (ΔT < −10) at about the same rate (0.23 to 0.24) as the decision tree results (Table 2). Relying on visual indicators of defect reduced recovery to 0.46 to 0.51, but also reduced the inclusion of defects to 7 to 8 percent of all log sections. The graphical analysis (GA10) resulted in bucking farther from the snap than the decision trees. As a result, less volume was recovered (0.64) and fewer defective sections were included (17%) in the recovered log.

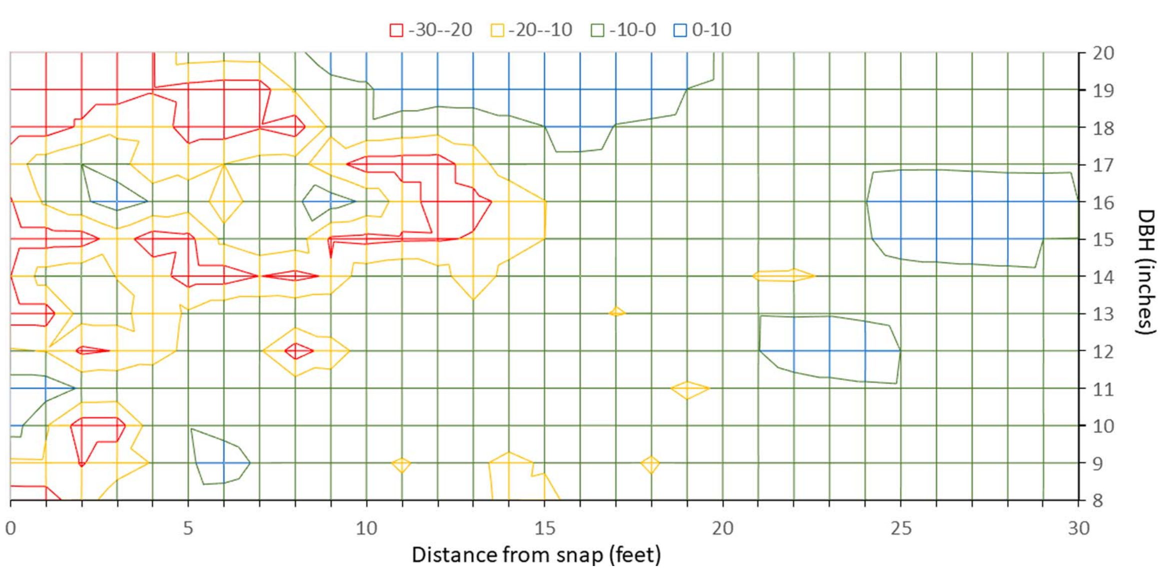

Figure 4.—Contour plot of values of deviation from reference velocity (ΔT) at observed level of diameter at breast height (DBH) in inches and distance from snap location in feet. Values result from proc g3grid with the spline option (SAS Institute 2016) for each inch and foot for DBH and distance, respectively.

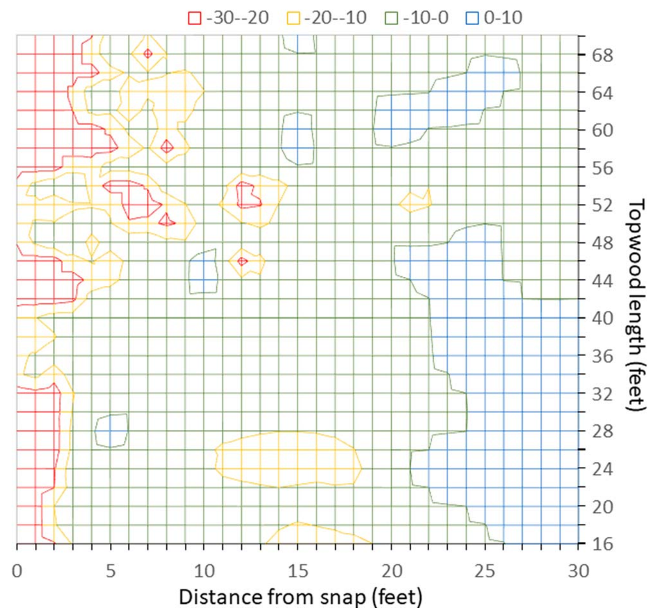

Figure 5.—Contour graph from values of deviation from reference velocity (ΔT) at observed level of topwood length in feet and distance from snap location in feet. Values result from proc g3grid with the spline option (SAS Institute 2016) for each inch and foot for diameter and distance, respectively (SAS Institute 2016).

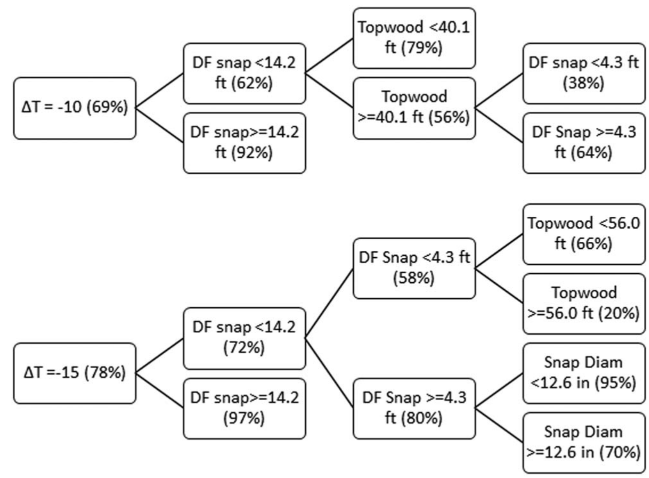

Figure 6.—Results from Proc HPSLIT using dependent variables deviation from reference velocity (ΔT) > −10 and > −15. Independent variables include distance from snap location in feet (DF snap), top wood length in feet (Topwood), and diameter at the snap location in inches (Snap Diam). Values in parenthesis are the percentage of sample locations that meet the criteria.

Across tree size (DBH) there was no obvious trend in recovery except for small trees (Fig. 7). For V4, V5, and V6 the bucking location sometimes resulted in logs that were too short to be recovered (<16 ft). For smaller trees (<12-in DBH) and 14-inch trees, the misclassification rate was similar for each method (Fig. 7). For larger trees V4 had the lowest rate of misclassification followed by GA10 and DT10. Since V4, V5, and V6 rely on close inspection of the log to identify the end of the damage, operational results are unlikely to be as accurate as these. Our inspection procedure would be difficult to replicate from an operator's station and in practice either the recovery would be lower or more defects would be included. The first, second, and third measurement locations had defect indicators on 60, 43 and 21 percent of the stems, respectively, indicating the difficulty of finding the end of the defect even on close inspection.

Table 2.—Model results for PROC HPSPLIT for ΔT levels −10 and −15.[a]

	ΔT = −10		ΔT = −15	
Model attributes	Training	Validation	Training	Validation
Misclassification	0.21	0.28	0.16	0.12
Sensitivity	0.52	0.41	0.44	0.42
Specificity	0.92	0.82	0.95	0.95
ASE	0.15	0.2	0.11	0.1
RSS	92.5	26.5	70.3	14.06
AUC	0.81	0.68	0.86	0.83
Relative importance				
Topwood (ft)	1	1	0.89	1
Snapdist (ft)	0.54	0.69	1	0.63
SnapDiam (in)	0.98	0.53	0.74	0.29

[a] ΔT = deviation from reference velocity; ASE = Average square error; RSS = Residual sums of squares; AUC = area under the curve; Topwood = log length from snap location to a 6-inch top; Snapdist = distance from the snap location; SnapDiam = diameter at the snap location.

Discussion

Splits and compression failure produce structural problems in lumber, but compression failures are difficult to visually identify. In storm-damaged Norway spruce (*Picea abies*) compression failures significantly affected lumber quality (Sonderegger and Niemz 2004, Arnold and Steiger 2007). There are no published data on the incidence of splits and compression failures from salvaged wind damaged southern yellow pine (*Pinus spp.*). Peralta et al. (1993) indicated that the cull logs delivered to a plywood mill affected mill operations, but the type of cull was not indicated. Following Hurricane Ivan, significant, but not visible, fiber damage was present in 15 to 30 percent of salvaged logs (Alabama Forest Recovery Task Force 2008).

Part of the damage, which is not visible, is in splits that are too small to identify or hidden under intact bark. Compression failures are even more difficult to visually identify but are present around the point of stem failure (Mergen 1954). Bucking at some distance from the point of failure is likely to remove both splits and some of the points of compression failure. Compression failures could occur throughout stems, even in standing trees that experience wind damage, but the evidence of compression failures is difficult to detect (Faust et al. 1994). Identification of compression failure might be difficult because the failure mode can consist of densified wood resulting in no visible cracking for field personnel to observe.

Evidence for determining the impact of the current bucking rules is limited. Nieuwenhuis and Fitzpatrick

Table 3.—Bucking results across all sampled trees.

Bucking method	Code	Volume recovered	Volume weighted velocity (m/s)	Ratio of defect sections included in log
Distance from split (4 ft)	V4	0.55	2,526	0.07
Distance from split (5 ft)	V5	0.51	2,715	0.07
Distance from split (6 ft)	V6	0.46	2,717	0.08
Measured at $\Delta T < -10$	M10	0.79	2,858	0.00
Results of decision tree ($\Delta T > -10$)	DT10	0.79	2,691	0.23
Results of decision tree ($\Delta T > -15$)	DT15	0.82	2,684	0.25
Graphical analysis ($\Delta T > -10$)	GA10	0.63	2,696	0.17

[a] ΔT = deviation from reference velocity; V4 = bucking at 4 feet from the end of the visible damage; V5 = bucking at 5 feet from the end of the visible damage; V6 = bucking at 6 feet from the end of the visible damage; M10 = value of ΔT was less than -10; DT10 = bucking using the decision tree rules at $\Delta T < -10$; DT 15 = bucking using the decision tree rules at $\Delta T < -15$; GA10 = logs bucked at 4 feet from snap when ≤12.5 inches in diameter at snap location and at 8 feet for trees >12.5 inches.

(2002) estimated that bucking scenarios could recover about 70 percent of comparable stem volume and a loss of about 24 percent of merchantable stems. In the salvage process, they indicated that bucking was adjusted so that there were no milling losses, but those adjustments were not described. Similarly in aspen (*Populus tremula*) salvage operations, about one-third of total stem volume across all stem sizes was lost (Čakša et al. 2021). Post-windstorm assessments in the United States are difficult to parse since the recovery of saw-timber volume includes damaged standing trees, wind-thrown trees, and broken trees. Most of the saw-timber volume is likely to come from the first two damage classes and broken trees are most likely to be marketed in whole or partially as pulpwood. The techniques we describe to change bucking procedure are difficult to evaluate economically since the state of current practices are undocumented except in general ways. The alternative methods described increase the retention of larger-diameter wood while producing similar quality wood considering the uncertainty of locating the end of visible damage.

The analysis is based on the ability of acoustic velocity to identify stem defects as a departure from the maximum stem value (Wang et al. 2004). While all the stems included in the study appeared to be free of internal decay, other kinds of defects in addition to split may have been detected (Xu et al. 2018). Particularly, the apparent defects that occurred at some distance from the snap location (>14 ft) in larger trees could indicate other kinds of defects. Additionally, the number of measurement points attempted (four) at each stem location would identify only larger defects. Acoustic techniques would probably be unable to identify compression failures, which are likely to extend beyond the point of stem failure (Sonderegger and Niemz 2004). More broadly applied, acoustic techniques might be able to aid log separation and marketing in conditions (Wang et al. 2013) with highly variable log quality due to storm damage as well defects from insects and decay as salvage activities progress beyond the date of the weather event.

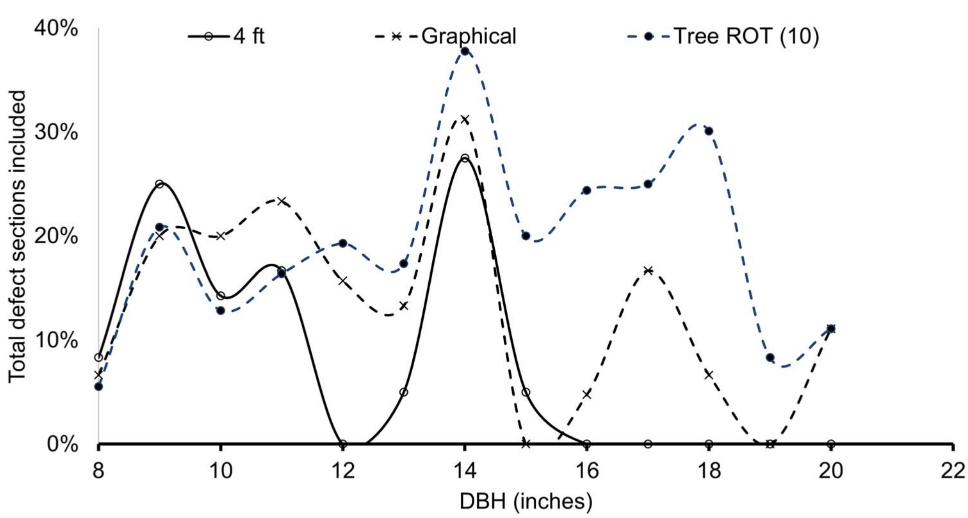

Figure 7.—Defect (deviation from reference velocity [ΔT] $<-10\%$) sections included in bucked logs using different bucking alternatives: 4 foot from last visible damage (4 ft), the rule built from Figure 5 data (Graphical), and the rules from HPSPLIT tree in Figure 6 ($\Delta T = -10\%$) (Tree Rule of Thumb (ROT) [10]). Results are summed by diameter class.

Conclusions

Identifying the extent of damage in wind-damaged logs with acoustics shows that salvageable volume extends closer to the breakage location than previous rules of thumb would indicate. Additionally, distance from the snap location, and size of the top (diameter and length) are simpler metrics to apply in real time by loader/processor operators. For stems with sawlog or veneer products, operationalizing acoustic measurements might be more practical. Given the distribution of defects, it is very difficult to build a visual rule that eliminates all defects in the salvaged top wood. Since there are so few data on how salvage bucking decisions are applied, the impact of changing bucking metrics is unknown. Additionally, this study demonstrates that acoustics may be a more accurate classification method than visual rules of thumb currently used by operators.

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