Sixteen stands were harvested by either clearcut, shelterwood, group selection, or single-tree selection methods. Harvesting operations were evaluated in four consecutive years (1991 through 1994). Three of the stands had uneven-aged structure, the other 13 were typical, mature, even-aged stands. Harvest intensity (proportion of basal area removed) ranged from 0.27 to 1.00. Logging contractors used one to three sawyers with production chain saws to fell trees and up to two rubber tired skidders (cable and or grapple). Harvested sites were similar in slope, average diameter at breast height (DBH) and pre-harvest number of stems by two inch diameter class.

There was no statistical difference in production rate between sawyers on the same stand. Total felling time per tree was inversely related to harvesting intensity and directly related to stem DBH. Factors affecting total felling time (in decreasing order of importance) were DBH of harvested stems, intertree distance, and harvest intensity. Grapple skidders operated significantly faster than cable skidders. Total skidding time per drag was also inversely related to harvesting intensity. Factors affecting total skidding time (again in decreasing order of importance) were skidding distance, skidder type (cable or grapple), harvesting intensity, load volume and number of stems in the load.

Productivity (100 cubic feet/hour) for both felling and skidding was found to be highest under high intensity harvests of large trees and lowest under low intensity harvests of small trees. Felling and skidding costs were shown to have an inverse relationship with productivity. Harvesting costs and productivity were more sensitive to stem diameter than harvest intensity.
INTRODUCTION

Comparisons of even-aged and uneven-aged forest management have recently attracted increased attention. One aspect of research includes comparisons of the time required to perform various timber harvesting operations under differing management regimes. Manual tree felling is the most labor intensive component of all harvesting operations, and frequently represents a "bottle neck" in production. Skidding machinery represents the biggest capital investment for most operators. Felling and skidding efficiency are dependent on stand conditions and harvesting prescription and were therefore chosen as the focus of this study.

Previous studies often addressed only a single harvest method, (i.e., clear cutting or single-tree selection) (Kellog et al., 1991; Miller and Sarles, 1986) with differences among stands or harvesting crews and equipment confounded with treatment effects (Bell, 1989; Miller and Smith, 1991; Sloan, 1991). Studies have been needed which cover both even-aged and uneven-aged silviculture and contain a large enough data set to identify trends common to harvesting operations. The results of timber harvesting time studies conducted over four years are presented here.

METHODS

Treatment of the Stands

A wide range of harvest intensities were examined. Clearcutting and single-tree selection methods represented extremes in harvest intensity, while shelterwood and group selection harvests represented intermediate treatments. Table 1 shows the method of harvest, harvest date, and harvest intensity. The proportion of basal area removed was used as an index of harvesting intensity for each stand. Basal area removed was chosen because it is sensitive to both number of trees removed from the stand and average tree size. Stands were located in western Arkansas (13 on the Ouachita National Forest and three on land owned by Deltic Farm and Timber Corporation).

The stands were composed primarily of shortleaf pine (Pinus echinata Mill.) and loblolly pine (Pinus taeda L.). There was a small hardwood component in all stands. The stands harvested in 1994 were of uneven-aged structure, while the other 13 were even-aged.

All stands were cruised before and after harvest to determine the harvest intensities. Diameter distributions from pre-harvest cruises were compared using a Kolmogorov-Smirnov distribution test (Wilkinson, 1990) to determine whether they were from the same parent distribution.
Table 1. Descriptive information for the 16 harvested stands.

<table>
<thead>
<tr>
<th>Stand (year-#)</th>
<th>Harvest Method</th>
<th>Proportion of BA (ft²/acre) Removed</th>
<th>Avg.DBH (inches) Removed</th>
</tr>
</thead>
<tbody>
<tr>
<td>91-01</td>
<td>Clearcut</td>
<td>1.00</td>
<td>11.4</td>
</tr>
<tr>
<td>91-02</td>
<td>Shelterwood</td>
<td>0.57</td>
<td>10.4</td>
</tr>
<tr>
<td>91-03</td>
<td>Single-tree</td>
<td>0.31</td>
<td>10.7</td>
</tr>
<tr>
<td>92-04</td>
<td>Clearcut</td>
<td>1.00</td>
<td>10.4</td>
</tr>
<tr>
<td>92-05</td>
<td>Shelterwood</td>
<td>0.71</td>
<td>10.6</td>
</tr>
<tr>
<td>92-06</td>
<td>Single-tree</td>
<td>0.43</td>
<td>13.7</td>
</tr>
<tr>
<td>93-07</td>
<td>Group</td>
<td>0.62</td>
<td>11.7</td>
</tr>
<tr>
<td>93-08</td>
<td>Group</td>
<td>0.48</td>
<td>10.9</td>
</tr>
<tr>
<td>93-09</td>
<td>Single-tree</td>
<td>0.45</td>
<td>13.5</td>
</tr>
<tr>
<td>93-10</td>
<td>Single-tree</td>
<td>0.32</td>
<td>13.9</td>
</tr>
<tr>
<td>93-11</td>
<td>Single-tree</td>
<td>0.31</td>
<td>11.8</td>
</tr>
<tr>
<td>93-12</td>
<td>Single-tree</td>
<td>0.30</td>
<td>12.2</td>
</tr>
<tr>
<td>93-13</td>
<td>Single-tree</td>
<td>0.27</td>
<td>12.3</td>
</tr>
<tr>
<td>94-14</td>
<td>Single-tree</td>
<td>0.36</td>
<td>15.5</td>
</tr>
<tr>
<td>94-15</td>
<td>Single-tree</td>
<td>0.32</td>
<td>15.5</td>
</tr>
<tr>
<td>94-16</td>
<td>Single-tree</td>
<td>0.27</td>
<td>16.0</td>
</tr>
</tbody>
</table>

The sawyers fell all marked trees within the stand boundaries according to felling ease and safety. Directional felling to optimize skidding was not a consideration, nor was it practiced. Hung trees occurred in all stands. When trees were hung, the sawyer stopped work while a skidder was used to pull or push the tree to the ground or the sawyer moved to a new area until the hung tree was brought to the ground by the skidder operator. Trees were processed into tree-length stems by limbing and topping immediately after felling. Felling and skidding operations worked in concert in the same general area of the stands at the same time.

Extreme care was taken to ensure that the research crew did not interfere or influence the harvesting operation. Researchers remained a safe distance from both the sawyers and the skidders until the operator had finished his work and it was safe to approach and measure the downed or piled stems.

Felling

A felling observation was defined as the time required for the sawyer to walk to a tree (walk), clear the brush for a safe exit path and plumb the tree (acquire), fell the tree (fell), and limb and top the tree (limb and top). Not every felling cycle was observed. Observed felling cycles were randomly chosen as work progressed through the stand. Field research team members timed and recorded each event in the cycle. When a tree was limbed and topped so it was safe to approach, researchers measured the diameter at breast height (DBH) and merchantable length (5-inch top) of the felled tree. Individual tree volumes were calculated by a formula developed by Clark and Saucier (1990). Total time per tree (excluding delays) was calculated for each observation. Means for walk-time, acquire-time, cut and limb and top-time were computed by tract and for the overall study. Differences in mean times were detected by Tukey's HSD pair-wise comparison test at the 0.05 level. Adjusted (for mean tree diameter and intertree distance) total-time-per-tree
was calculated for each stand. A nonlinear regression model was estimated for total felling time with the percentage basal area harvested, DBH and intertree distance as independent variables. Two additional nonlinear models were developed to predict productivity (CCF/hour) and cost ($/CCF) using the same independent variables. The cost estimation incorporated machine rate calculations (Miyata, 1980) and productivity estimates.

Skidding

A complete skidding cycle was composed of travel empty-time, bunch building-time, travel loaded-time and deck-time. A random sample of skidding cycles was observed on each stand. Components of the skidding cycle were timed separately. The distances the skidder traveled while empty, building a bunch and loaded were measured for each cycle. After the skidder deposited and piled the stems at the deck, the stems' DBH and length were measured.

Analysis of the skidding data followed a similar pattern to that of the felling data. A regression equation was calculated to model total skidding time. Independent variables considered in the analysis included total distances traveled, number of stems in the load, average DBH of the stems in the load, volume of the load, harvest intensity, skidder type, skidder horse power, and system task proficiency (STP). Skidder type and STP were binary variables. A stepwise regression process was used to identify variables significant at the 0.01 level.

STP was first developed as a subjective evaluation of crew aggressiveness. It had a value of one in crews that worked quickly through the stand and zero for crews that worked more slowly. When this variable was added to the data set, it became apparent that it also captured variability caused by the level of mechanization and the harvest intensity. Operations with at least one grapple skidder tended to be placed in the high STP category. High intensity harvests were more commonly classified as high STP. Therefore, it was not just an evaluation of the logging crew but of the entire logging system on a given stand.

Nonlinear models for skidding productivity and cost were also developed. These models focused on variation caused by average stem DBH and harvest intensity. A 95 horse power grapple skidder was used as a “typical” skidder in creating these equations.

RESULTS

Stands

The pre-harvest diameter distributions were compared using a Kolmogorov-Smirnov distribution test which showed that they were from the same parent distribution. The diameter distribution for the three uneven-aged stands harvested in 1994, while not statistically different from the parent population, were approaching a “reverse-j” distribution indicative of uneven-aged stands. The average harvested stem DBH was larger in these stands. This is a function of the uneven-aged management prescription where the harvested trees are concentrated in the larger DBH classes. In the seven even-aged stands harvested by single-tree selection, the
distribution of removed stems was similar to a mixed thinning with cutting in the 6- to 10- inch classes (low thinning) and in the 14- to 18- inch classes (thinning from above). The goal of this thinning was to move these stands toward uneven-aged structure.

Felling

Each phase of the felling operation was fit to an exponential equation \( Y = a \cdot X^b \) using DBH as the independent variable. This was done to determine whether or not the results of the current study were consistent with classic relationships defined in the literature.

Intertree distance was inversely related to harvesting intensity. The sawyer had to walk further to find marked trees in the single-tree selection stands than in the clearcut stands where he could move directly to the next nearest tree; walk-time decreased as harvesting intensity increased. The number of trees marked on a per-acre basis was influenced by the size of the trees. The distance between trees may be approximated by the square root of the area per tree. Thus, a square root relationship between walk time and DBH as found (the exponent coefficient approaching 0.5) is consistent with expected relationship.

\[
\text{Walk Time} = 0.076 \cdot \text{DBH}^{0.591}
\]

There was no identifiable trend in acquire-time. The amount of time to plan the direction the tree was to fall and to clear brush from around a ten inch tree would be about the same as that of a twenty inch tree. Only in the extreme diameter classes would DBH have an influence on acquire time. The low power coefficient shows that in the observed cycles this value was essentially constant. An exponent of zero would mean that acquire time is constant independent of the size of the tree.

\[
\text{Acquire Time} = 0.080 \cdot \text{DBH}^{0.200}
\]

Fell time approached a linear relationship with the DBH (the exponent coefficient approaching one). This is consistent with studies evaluating production chainsaws (Lanford et al., 1972).

\[
\text{Fell Time} = 0.047 \cdot \text{DBH}^{0.937}
\]

Limb and top time was a function of crown size. The ratio of crown diameter to stem diameter is essentially constant; therefore stem volume may be estimated as a function of crown diameter (Avery and Burkahart, 1983). It is reasonable that the time to remove the limbs and top (a function of crown size) would be estimated using the best single proxy for stem volume, which is \( \text{DBH}^2 \). Limb and top time constituted the largest portion of the felling operation.

\[
\text{Limb and Top Time} = 0.006 \cdot \text{DBH}^{2.129}
\]

Figure 1 shows total felling time broken into each component. The vertical distance between the lines is the average time required for the identified activity. The top line is the average total felling time based solely on DBH.

\[
\text{Total Time} = 0.069 \cdot \text{DBH}^{1.379}
\]

\[ R^2 = 0.49 \quad n = 1150 \]
Figure 1. Predicted felling time by operation for a tree based on Diameter at Breast Height.

Stem diameter proved to be the most significant variable when estimating felling time of a tree independent of stand characteristics and harvesting prescription. When estimating the felling time of a tree within a stand, the distance from the previous felled tree (DIST) and the proportion of basal area removed (INTENSITY) also proved to be significant at the .01 level.

\[
\text{Total Time} = 1.049 + 0.009 \cdot \text{DBH}^2 + 0.006 \cdot \text{DIST} - 0.850 \cdot \text{INTENSITY} \\
R^2 = 0.55 \quad n = 1145
\]

Table 2 gives the range of values for harvest intensity, intertree distance, and DBH which were the significant independent variables. Other factors were tested as possible independent variables but were not significant.

<table>
<thead>
<tr>
<th>Table 2. Summary of felling data variables used in the stand level felling regression equation based on 1154 observations.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variable</td>
</tr>
<tr>
<td>Proportion of Basal Area Removed</td>
</tr>
<tr>
<td>DBH Removed (inches)</td>
</tr>
<tr>
<td>Intertree Distance (feet)</td>
</tr>
</tbody>
</table>

Application of the total time regression equation is straightforward. For example, a 15-inch tree versus a 10-inch tree would take 1.125 minutes longer to process (all other conditions being the same). The sensitivity of the time estimate to each independent variable was evaluated
through the use of standardized coefficients. These coefficients have been adjusted to remove differences in scale by using means and standard deviations. Examination of the standardized coefficients in the structural regression equation indicated the most important factors influencing total felling time (in decreasing order of importance) were DBH, intertree distance, and harvest intensity. The expected total times per tree for each stand are plotted in Figure 2 using individual stand averages for DBH, intertree distance and measured harvest intensity (points). The line in Figure 2 shows the expected total felling time across all harvest intensities using global averages (all stands combined) for DBH and intertree distance.

![Graph](chart.png)

Figure 2. Predicted felling times for trees within a stand.

Productivity in hundred cubic feet (CCF) per hour was calculated using measured total time and estimated stem volume. An estimator for productivity was derived using a nonlinear model with DBH and harvest intensity as the independent variables.

\[
CCF/HR = 1.627 \cdot DBH^{0.628} \cdot INTENSITY^{0.209}
\]

Figure 3 shows the response surface produced by this model. Removal intensity had less influence on productivity than DBH.

Felling cost per unit volume varied directly with productivity. An hourly fixed cost of $0.30, a variable cost of $0.70 per productive hour, and a labor cost of $7.98 per hour were used in calculations. The adjusted (50 percent availability) (Miyata, 1980) hourly operating cost under these assumptions was $17.56 per hour. The response surface for the relationships between cost,
Figure 3. Felling productivity by harvest intensity and diameter at breast height.

DBH and harvest intensity (Figure 4) was the inverse of the productivity surface with the differences in slope being influenced by the machine rate estimate. (Note that the DBH axis is reversed in Figure 4 to facilitate viewing the surface.) The cost of harvesting small trees was more sensitive to the harvest intensity than the cost of harvesting large trees.

Skidding

The independent variables found to be statistically significant at the 0.01 level in estimating total skidding time were total distance traveled (TDIST), number of stems in the load (STEMS), volume of the load (VOL), proportion of basal area removed (INTENSITY), skidder type was one for grapple and zero for cable (SKID), skidder horsepower (HP), and system task proficiency (STP). The coefficients for TDIST, VOL, SKID and HP were dependent on the value of STP. The equations below come from a single linear regression model, but reflect these differences.

High STP
\[ TT = 4.699 + 0.003 \cdot TDIST + 0.369 \cdot STEMS + 0.008 \cdot VOL - 2.748 \cdot INTENSITY - 1.581 \cdot SKID \]

Low STP
\[ TT = 4.699 + 0.006 \cdot TDIST + 0.369 \cdot STEMS + 0.032 \cdot VOL - 2.748 \cdot INTENSITY - 0.026 \cdot HP \]

\[ R^2 = 0.630 \quad n = 1107 \]
There were no grapple skidders used in operations which had a low STP, so skidder type was not applicable. There were cable skidders working in high STP operations. These cable skidders were typically working in conjunction with grapple skidders. Skidder horsepower was not significant in operations with high STP. Table 3 gives the range of values observed for each non-binary independent variable. These equations are illustrated in Figure 5, where all independent variables except for skidder type, STP and harvest intensity are held at their global means.

<table>
<thead>
<tr>
<th>Variable</th>
<th>max.</th>
<th>min.</th>
<th>mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proportion of Basal Area Removed</td>
<td>1.00</td>
<td>0.27</td>
<td>0.58</td>
</tr>
<tr>
<td>Load Volume (feet(^3))</td>
<td>108.9</td>
<td>53.8</td>
<td>77.4</td>
</tr>
<tr>
<td>Stems per Load</td>
<td>14</td>
<td>1</td>
<td>3.7</td>
</tr>
<tr>
<td>Horsepower</td>
<td>130</td>
<td>72</td>
<td>108</td>
</tr>
<tr>
<td>Skidding Distance (feet)</td>
<td>344</td>
<td>23</td>
<td>131</td>
</tr>
</tbody>
</table>

Grapple skidders took about 1.5 minutes less per cycle than cable skidders. High STP crews were able to handle the same size load almost four times faster than low STP crews, and traveled twice as fast over the same distance.
Figure 5. Estimated skidding time per cycle by harvest intensity (other independent variables are held at their global means).

\[
CCF/HR = 1.685 \cdot DBH^{1.409} \cdot (12.991 \cdot DBH - 3.721 \cdot INTENSITY)^{-1}
\]

Skidding productivity (CCF/HR) estimated for a 95 horse power grapple skidder revealed a strong positive relationship with stem DBH and an inverse relationship with harvesting intensity. Figures 6 and 7 show these relationships graphically. In Figure 6, DBH is on the x-axis and various levels of harvest intensity are shown as anamorphic curves. Figure 7 depicts harvest intensity on the x-axis and DBH as a family of anamorphic curves. Figure 8 is the productivity response surface created by a three dimensional rendering of these relationships.

Figure 6. Estimated skidding productivity for all diameters at specific harvest intensities (proportion of basal area removed).
Figure 7. Estimated skidding productivity for all harvest intensities at specific diameters.

Figure 8. Skidding productivity by harvest intensity and diameter at breast height.
Skidding productivity followed the same general pattern found for felling. Productivity was highest when large trees were harvested at high intensities, and was more sensitive to DBH than to harvest intensity.

The machine rate calculation for cost estimation was based on a 95 horsepower grapple skidder. Fixed costs were computed as $20.93 per hour. Variable costs assuming 66% availability (Miyata, 1980) were $43.59 per hour. These estimates combined with the productivity equation yield the response surface in Figure 9. Costs were relatively low in the larger diameter classes, but rose sharply in the smaller diameters. The critical diameter where costs began to increase at an increasing rate was larger at low intensities than at high intensities.

![Figure 9. Skidding cost per 100 cubic feet by harvest intensity and diameter at breast height.](image)

DISCUSSION

Felling

The most important factors in felling time per tree were DBH, intertree distance and harvest intensity. In the analysis of co-variance and the structural regression analysis, intensity acted as a harvest variable to collect variation in felling time. The extra time spent finding marked trees, planning the cut, and working around residual stand components slowed production for the partial harvest methods.
Individual tree size had the greatest influence on felling productivity. The felling operation was most productive and least expensive (per unit of volume) in stands were large trees were being removed under high harvest intensities. The average DBH removed from the even-aged stands tended to be lower than those from the uneven-aged stands. The even-aged stands were characterized by a normal bell shaped distribution of tree size. Trees removed from these stands tended toward the stand average tree size. In the uneven-aged stands, the tree size distributions approached a "reverse-j" with many more stems in the smaller diameter classes than in the larger classes. At harvest, only the larger diameter classes were removed (this is typical of uneven-aged forest management). This had the effect of increasing productivity (CCF/hour) and reducing costs ($/CCF) even at the observed lower harvesting intensities.

Skidding

Skidding time, productivity, and cost per unit volume were significantly influenced by the average tree size removed, the harvest prescription and the skidding equipment and crew.

When harvesting larger trees, fewer stems were required to fully load the skidder, thus allowing the operation to skid more volume per unit of time. Skidders were more apt to be fully loaded when working with large stems.

- The intensity of the harvest as laid out in the harvesting prescription influenced the amount of time required for the skidder to build a full load. At low intensities, the skidder was required to travel farther to build a load than at high intensities. Maneuvering was difficult and time consuming in stands where a large number of trees were left standing.

Grapple skidders consistently operated faster than cable skidders. Crews which used both a cable and grapple skidder utilized the cable skidder more effectively than crews using only cable skidders. The horsepower of the skidder was statistically important in predicting skidding time only for a cable skidder operating by itself. It was in these operations where higher power skidders significantly reduced cycle time.

Many of the factors which differentiated one crew's proficiency from another's were not easily quantified. Researchers used their experience to categorize crews as having low or high system task proficiency. These categories were purposefully broad so that anyone familiar with logging operations would arrive at the same basic classification. This subjective evaluation turned out to be influenced interactions between the type of machinery used, the harvest intensity and the crews' aggressiveness. The STP variable was statistically significant in predicting skidding time.

CONCLUSIONS

Light thinnings of small trees were the most expensive per CCF harvested. Harvesting large trees even at lower intensity produced a lower $/CCF than when smaller trees were harvested. For example, stand 93-13 had an average DBH harvested of 11.5 inches and an intensity of 0.27 proportion of basal area removed, while in stand 94-16 the average DBH removed was 16.23 inches at the same harvest intensity (0.27). The response surface analysis indicates that it would be less expensive per CCF to harvest stand 94-16.
Harvesting time and cost were directly related to harvest intensity and inversely related to DBH of harvested trees. Harvesting productivity was directly related to DBH of removed stems and inversely related to harvest intensity. These relationships followed expected patterns. What was not expected was the relative importance of DBH over harvest intensity. Across all stands, the most important factor influencing harvesting efficiency was harvested tree size.

The controversy between even-aged versus uneven-aged management and their associated silvicultural methods will continue, especially for public land management. For many proponents of uneven-aged management, harvesting cost and economic efficiency are a distant third consideration after maintaining stand visual quality and minimizing individual stand disturbance. Even-aged management advocates focus on harvesting and capital efficiency as preeminent concerns.

An extension of this analysis will be to identify profitability of harvesting operations given different values of logs at the mill. The stand conditions and harvest prescription at which an operation is economically feasible needs to be shown.

LITERATURE CITED


