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Abstract

Sixteen stands were harvested by either clearcut, shelterwood, group selection, or single-tree selection methods. Harvest productivity was 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 on all 16 tracts. There was no statistical difference in production rate between sawyers on the same stand. Harvested sites were similar in slope, average diameter at breast height (DBH) and pre-harvest number of stems by two inch diameter class. Total felling time (including walk, acquire, fell, and limb-top times) 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. Felling productivity (100 cubic feet/hour) was found to be highest under high intensity harvests of large trees and lowest under low intensity harvests of small trees. Productivity was more sensitive to stem diameter than harvest intensity. Felling cost was shown to have an inverse relationship with felling productivity.

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. 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 all manual felling operations. The results of felling time studies conducted over four years are presented here.

Materials and 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).

Table. 1. Descriptive information of the 16 stands studied.

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

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.

The sawyers felled 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.

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, limb and top-time, and delay-time were computed by tract and the overall study. Differences in mean times by sawyer and harvest year were detected by Tukey's HSD pair-wise comparison test at the 0.05 level. Adjusted (by mean tree diameter and intertree distance) total-time-per-tree was calculated for each stand. A linear regression model was estimated for total felling time with the proportion 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 just harvest intensity and DBH. The cost estimation incorporated machine rate calculations. (Miyata, 1980) and productivity estimates.

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 the 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 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 and 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 DBH^2. Limb and top time constituted the largest portion of the felling operation.

$$\text{Limb and Top Time} = 0.06 \cdot DBH^{2.129}$$

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.

$$\text{Total Time} = 0.069 \cdot DBH^{1.379}$$
$$R^2 = 0.49 \quad n = 1150$$

Tree 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 provided to be significant at the .01 level.

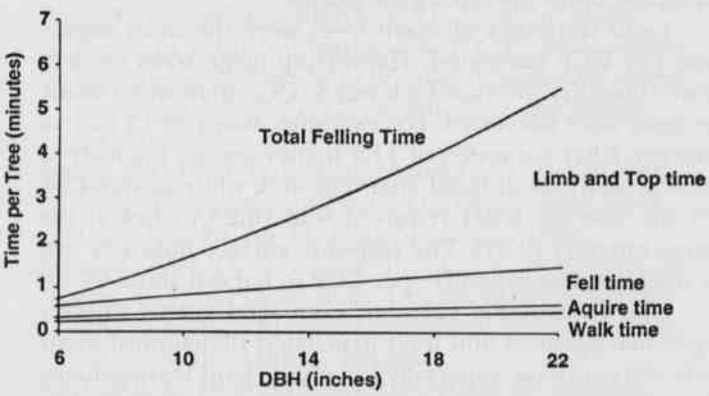

Fig. 1. Predicted felling time by operation for a tree based on Diameter at Breast Height.

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

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

Table 2. Summary of the felling data variables used in the stand level felling regression equation based on 1154 observation.

Variable	max.	min.	mean
Intensity (% basal area)	1.00	0.27	0.49
DBH Removed (inches)	26.1	5.2	13.7
Intertree distance (feet)	408	1.1	43.2

Application of the total time regression equation is straightforward. For example, a 15-inch tree would take 1.125 minutes longer to process (all other conditions being the same) than a 10-inch tree. 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 Fig. 2 using individual stand averages for DBH, intertree distance and measured harvest intensity (points). The line in Fig. 2 shows the expected total felling time across all harvest intensities using global averages (all stands combined) for DBH and intertree distance.

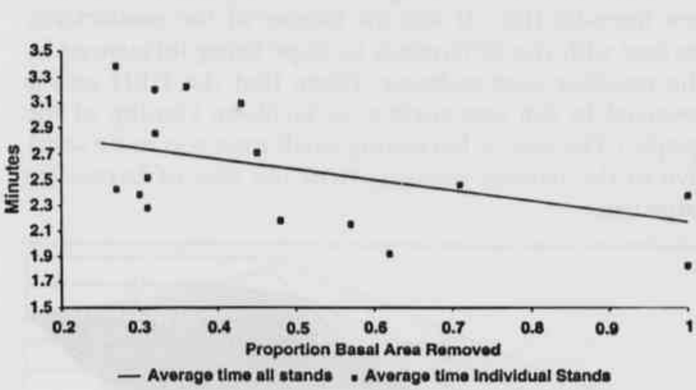

Fig. 2. Predicted felling times for trees within a stand.

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.

$$CCF/HR = 1.627 \cdot DBH^{0.628} \cdot INTENS^{0.209}$$

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

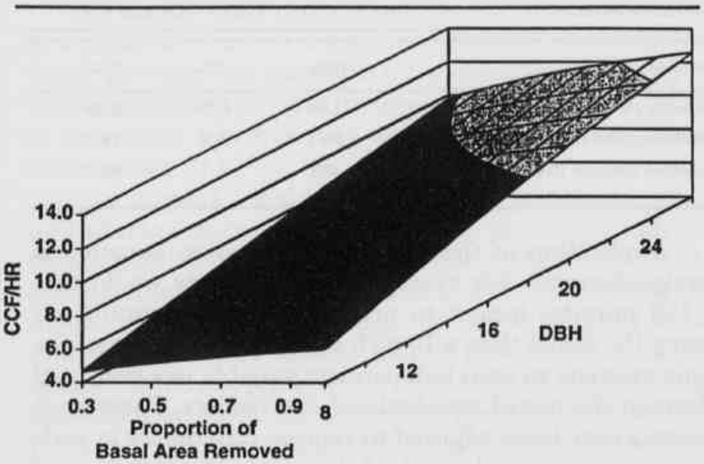

Fig. 3. Gelling productivity by harvest intensity and diameter at breast height.

Felling cost per unit volume varied inversely 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, DBH and harvest intensity (Fig. 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 the cost surface to facilitate viewing of the graph.) The cost of harvesting small trees was more sensitive to the harvest intensity than the cost of harvesting large trees.

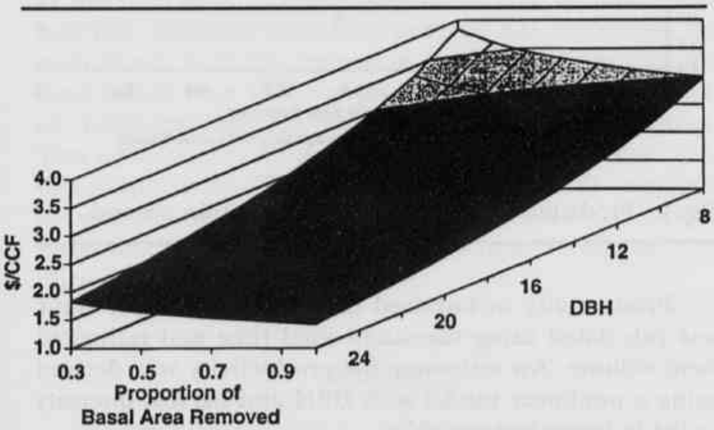

Fig. 4. Felling cost per 100 cubic feet by harvest intensity and diameter at breast height.

Discussion

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 caused by harvesting prescription. 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 where 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.

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 intensity (0.27). The response surface indicates that it would be less expensive per CCF to harvest stand 94-16.

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 felling operations given different values of logs at the mill. The stand conditions and harvest prescription at which an operation is economically feasible need to be shown.

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