Felling and Skidding Productivity and Harvesting Cost in Southern Pine Forests

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ABSTRACT - Sixteen stands were harvested at various levels of basal area removed (intensity). Chainsaw felling productivity was more sensitive to stem diameter than harvest intensity. Skidding productivity was highest when removing large trees at high intensity. Harvesting cost was more sensitive to stem size than harvest intensity although harvest intensity was a very important factor in cost of removing small stems.

INTRODUCTION

The current interest in sustainable forestry has significant implications for harvesting operations. The concept of sustainability implies reducing the effect of harvesting on residual stand components, maintaining long term productivity of the forest, operating on as few hectares annually as possible, and the ability to harvest and process timber as profitably as possible for some indefinitely long period of time. Accordingly. managers will be increasingly concerned with the interplay between felling and skidding machinery and the stand.

For most actively managed forest holdings a broad scale management plan drives a site-specific silvicultural prescription. Site specific prescriptions, in turn, dictate the harvesting plan. The study that we report here is the result of observing harvesting operations on 16 tracts in western Arkansas, USA, over a four-year period. These operations reflected a broad variety of harvesting prescriptions. This paper presents an analysis of more than 1,100 felling and 1,050 skidding cycles.

Harvesting equipment needs to be as productive as possible. For example, efficiency of skidding operations is dependent on having a skilled operator, mechanically sound equipment and a sufficient volume of logs to be skidded. But, skidding efficiency is also influenced by the stand conditions and the harvesting prescription. The influences that the pre-harvest stand conditions and harvesting prescription have over chainsaw felling and rubber-tired skidder productivity are the focus of this paper.

METHODS

Treatment of the Stands

The harvesting prescriptions in the study ranged from clearcutting to single-tree selection. Proportion of basal area removed was used as a quantitative index of harvesting intensity because it was sensitive to both number of trees removed from the stand and average tree size. The stands were composed primarily of shortleaf pine (*Pinus echinata* Mill.) and loblolly pine (*Pinus taeda* L.). There was a hardwood component in all stands but it did not limit the operations because of small stem size. Slopes were less than 15% and were not a limiting factor. Three of the stands harvested had 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-Smimov distribution test (Wilkinson 1990) to determine whether or not they were from the same parent distribution (e.g., they are representative of a single stand).

Directional felling to optimize skidding was not practiced. Trees were processed into tree-length stems by the sawyer 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 operators had finished their work.

Felling

Manual tree felling is the most labor intensive component of all harvesting operations. and frequently represents a "bottle neck" in production. While mechanical felling is typically more productive than manual felling, site disturbance and residual stand damage may be increased by the additional machinery operating on the stand.

A felling observation consisted of 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), cut the tree down (fell), and remove the limbs 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. After a tree was limbed and topped and it was safe to approach, researchers measured the diameter at breast height (DBH) and merchantable length (most stems were cut to a 13 cm 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. Differences in mean times by sawyer and harvest year were tested by Tukey's HSD pair-wise comparison test at the 0.05 level.

Table 1. Descriptive information for the 16 stands studied.

Stand	Harvest Method	Proportion of BA Removed	Avg. DBH Removed (cm)
91-01	Clearcut	1.00	28.96
91-02	Shelterwood	0.57	26.42
91-03	Single-tree	0.31	27.18
92-04	Clearcut	1.00	26.42
92-05	Shelterwood	0.71	26.92
92-06	Single-tree	0.43	34.80
93-07	Group Selection	0.45	79.72
93-08	Group Selection	0.62	27.69
93-09	Single-tree	0.45	34.29
93-10	Single-tree	0.32	35.31
93-11	Single-tree	0.31	29.97
93-12	Single-tree	0.30	30.99
93-33	Single-tree	0.27	31.24
94-14	Single-tree	0.36	39.37
93-15	Single-tree	0.32	39.37
93-16	Single-tree	0.27	40.64

Characteristics of the stand and harvest prescription were included in a model to determine how these factors influence total felling time and to give a more realistic model of the felling operation.

A nonlinear model was developed to estimate total felling time per tree. The nonlinear model was combined with a single entry volume estimating equation ($Vol = a \cdot DBH^b$) to give a nonlinear function estimating felling productivity.

Skidding

A complete skidding cycle consisted of travel empty, bunch building, travel loaded and deck-time. Components of the skidding cycle were timed separately. Distances 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 DBH and length of each stem were measured. A random sample of skidding cycles was observed on each stand.

Stem DBH and length measurements were used to calculate the average DBH in the load and the total volume of the load. The load volume was the sum of stem volumes. which were calculated using DBH and merchantable length (Clark and Saucier 1990).

Total skidding cycle time was estimated separately for grapple skidders. cable skidders operating in concert with grapple skidders and cable skidders operating alone. Independent variables considered in the analysis included total travel distance, number of stems in the load, average DBH of the stems in the load, volume of the load, harvest intensity, skidder type and skidder horsepower. A nonlinear equation was developed for each skidder-operation type using only independent variables which were significant at the 0.01 level.

Nonlinear models for estimating skidding productivity were also developed. These models combined the total skidding cycle time equation with an equation which estimated load volume based on average DBH and number of stems in the load. The load volume equations used the form:

$Vol = a \cdot DBH^b \cdot STEMS^c$.

RESULTS

Stands

The pre-harvest diameter distributions of samples taken compared to the stand distributions using a Kolmogorov-Smirnov distribution test showed that the samples were from the same parent distribution. The average harvested stem DBH was larger than the average stand DBH in all stands except the clearcuts. This was a function of the selection harvest prescriptions where the harvested trees were concentrated in the larger DBH classes.

Felling

Without delay times. there was no statistical difference in the rate different sawyers worked on the same stand. Thus. a variable for different sawyers was not needed or included in this analysis. Tree diameter proved to be the best single variable when estimating felling time of a tree. However, additional information regrading the stand's characteristics and harvesting prescription improved the prediction of felling time. Including the stand level factors (DIST, INTEN) in the mathematical equation produced a more realistic model of the felling operation.

When estimating the total felling time (TT) of a tree within a stand, the distance (m) from the previous felled tree (DIST), the proportion of basal area removed (INTEN) and stem diameter (DBH) proved to be significant at the 0.01 level.

$$TT = 0.016 \cdot DBH^{1.338} \cdot DIST^{0.083} \cdot INTEN^{-0.196}$$

$$R^2 = 0.55 \quad n = 1145$$

Other factors were tested as potential independent variables but were not significant at the 0.01 level. The predictive capability of this equation was significantly better than when using only DBH

An estimator for productivity (m’ per productive Hr) of chainsaw felling was derived by combining the nonlinear total time model with the single entry volume estimating equation.

$$\frac{m^3}{Hr} = 2.697 \cdot DBH^{0.668} \cdot DIST^{-0.083} \cdot INTEN^{0.196}$$

Skidding

Three operating groups were apparent based on the skidder type and operation organization. The cable skidders fell into two groups depending on whether or not there was a grapple skidder operating in conjunction with the cable skidder. The presence of a grapple skidder in the operation influenced how the cable skidders were operated and allowed them to be used more efficiently and aggressively. The presence of a cable skidder did not significantly alter the perfonance of the grapple skidders, so all grapple skidders were grouped together. Each of the three groups showed different relationships with the independent variables. In the case of cable skidders operating alone, a different set of independent variables was significant.

The independent variables found to be statistically significant at the 0.01 level in estimating total skidding time *were* total distance traveled (TDIST in meters), number of stems in the load (STEMS), harvest intensity (INTEN) and skidder horsepower (HP). However, INTEN was not significant for the cable skidders operating without grapple skidders. Additionally, HP was significant for only this group. The equations listed below estimate total cycle time (TT) in minutes for each of the three groups.

Grapple (all)

$$TT = 2.805 \cdot TDIST^{0.574} \cdot STEMS^{0.100} \cdot INTEN^{-0.113}$$
$$R^2 = 0.50 \quad n = 542$$

Cable (with Grapple)

$$TT = 3.438 \cdot TDIST^{0.399} \cdot STEMS^{0.190} \cdot INTEN^{-0.325}$$
$$R^2 = 0.61 \quad n = 315$$

Cable (alone)

$$TT = 143.243 \cdot TDIST^{0.453} \cdot STEMS^{0.295} \cdot HP^{-0.758}$$
$$R^2 = 0.64 \quad n = 240$$

The equations estimating productivity were a combination of the skidder cycle time model and a derived load volume equation. The load volume equation was based on the average DBH of the load and the number of sterns within the load. Thus, the combined equations include DBH and a coefficient for STEMS as well as TDIST and INTEN.

Grapple (all)

$$\frac{m^3}{Hr} = 0.017 \cdot TDIST^{-0.574} \cdot DBH^{2.002} \cdot STEMS^{0.865} \cdot INTEN^{0.113}$$

Cable (with Grapple)

$$\frac{m^3}{Hr} = 0.012 \cdot TDIST^{-0.399} \cdot DBH^{2.041} \cdot STEMS^{0.766} \cdot INTEN^{0.325}$$

Cable (alone)

$$\frac{m^3}{Hr} = 0.0006 \cdot TDIST^{-0.453} \cdot DBH^{1.814} \cdot STEMS^{0.477} \cdot HP^{0.758}$$

DISCUSSION AND APPLICATION

Productivity

For both felling and skidding productivity, the average size (DBH) of the harvested trees (stem volume) played a more significant role in determining productivity than did the intensity (MTEN) of harvest. However, bunch-building time for the skidders (proxied by STEMS) was also a major significant factor in determining total cycle time and productivity. The total cycle time and productivity equations emphasize the strongly interactive and nonlinear relationships involved in both felling and skidding. However, a discussion of these relationships and the partial derivatives of the associated hyperspace response surfaces is beyond the scope of this paper.

Harvesting Cost

Harvesting cost per unit volume ($\$/m^3$) by harvesting phase is derived from two major pieces of information: machine operating cost ($/Hr.) and productivity ($m^3$/Hr). The derivation of total unit cost is straight forward.

$$Total\ Cost\ \left(\frac{\$US}{m^3}\right) = \sum_{i=1}^{n} \left[\left(\frac{\$US}{Hr}\right)_i / \left(\frac{m^3}{HR}\right)_i\right] + C_i$$

Where: i=hourly cost and productivity for phase i

Operating cost per hour for felling, skidding, loading and hauling may be obtained through an empirical or theoretical approach. We used Miyata’s (1980) method to develop costs for each machine and phase. The adjusted (for 50%

mechanical availability) total hourly cost per productive hour for chainsaw felling was $US 17.56 and for skidding with a 95 HP grapple skidder (67% availability), $US 46.19. Total cost to load was estimated at $US 1.68/$m^3$ and a 73 Km, one-way hauling cost of $US 2.63/$m^3$ was assumed. Loading and hauling costs were held constant since their costs did not vary with the stand or prescription variables described above.

Estimated total costs to harvest and deliver the tree-length stems to a mill are detailed in Table 2 for various levels of harvest intensity and stem size. The common question of whether single tree selection harvesting costs are significantly higher than clear cutting is answered in Table 2.

Table 2. Cost ($US) to harvest and deliver (73 Km haul), m^3 of wood, by harvest intensity and harvested tree size.

	Harvest Intensity (proportion of basal area removed)			
DBH(cm)	0.25	0.5	0.75	1.00
15.2	14.72	13.85	13.37	13.05
20.3	10.61	10.06	9.77	9.57
25.4	8.66	8.26	8.06	7.91
30.5	7.56	7.26	7.09	6.99
35.6	6.88	6.63	6.05	6.41
40.6	6.42	6.22	6.11	6.03
45.7	6.10	5.92	5.82	5.76
50.8	5.86	5.70	5.62	5.56
55.9	5.68	5.53	5.46	5.41
61.0	5.53	5.40	5.34	5.28

The selection harvests that we studied ranged from 0.27 to 0.43 of the initial stand basal area removed. Group-selection and shelterwood harvests removed a higher percentage of the stand. If the average DBH of removed stems was 15 cm in a 25% removal, as in a first thinning of a pine plantation, an additional cost of SUS 1.67/m^3 (+13%) would be incurred over that of a clearcut (100% removal). However, if the average DBH of the removed stems was 61 cm, the additional cost for a 25% removal would only be SUS .25/m^3 (+5%) over the clearcut.

Further inspection shows that above a threshold tree size of about 30 cm DBH, estimated harvesting costs change little with tree size and almost not at all with harvest intensity. This result is somewhat surprising for clear cutting pundits and soothing to those who have always held that selection harvests can be performed as cheaply as more intensive harvests. However. caution must be exercised in applying these results. For example, thinning from below in artificially regenerated stands will seldom produce an average DBH of removed stems as large as 30 cm. Additionally, it is in the smaller diameter classes that harvest intensity has the greatest effect on productivity and hence. harvest cost. This is due to the increase in time required to build bunches for skidders and handle individual stems of low volume.

Although this study was limited to manual chainsaw felling, the principle would apply to mechanized felling operations as well. When harvesting a large number of low volume stems, (10 / m.^{3}) something must be done to increase the volume handled per unit time in order to keep unit cost acceptably low. Since machine hydraulic systems are limited in their cycle speed, large volume bunches must be handled at each cycle. This is true for both felling (feller-bunchers) and skidding.

Selection of Harvesting Equipment

There is yet an additional problem which relates to equipment selection. For single tree selection to work silviculturally. trees must be addressed individually in marking, and then in the harvest scheme. Further, harvesting in naturally regenerated stands compounds the problem Since a simple row thinning cannot be prescribed. If mechanized felling is to be used in selective harvest of naturally regenerated stands, then relatively small, tree-to-tree machines are required

An additional aspect of this four-year study was to determine the impact harvesting had on the residual stand. In our field observations it became clear that selection harvests in naturally regenerated. well-regulated uneven-aged stands would require a great deal of rethinking about how we handled the stems that we were removing, primarily because of the number of residual trees that were skidder damaged or otherwise mechanically disturbed.

The majority of the stands in which we observed the harvesting process were of even-aged origin being converted to uneven-aged management. Proponents of single tree selection point out that in established, well-regulated uneven-aged stands, the majority of the trees and volume to be removed will lie in the largest diameter classes. This is true. When harvesting these stands the economies of scale associated with processing larger stems pay large dividends. However, for sustainable forestry to be a practical concept, residual stand components must be protected. This calls for continued work on balancing equipment and harvesting techniques to specific harvest prescriptions. Although our study has shed some light on the relationship between removal intensity and tree size, the complex relations indicated in our productivity equations need to be further researched to better understand equipment requirements for a broad range of selection harvest techniques.

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