STAND, HARVEST, AND EQUIPMENT INTERACTIONS IN SIMULATED HARVESTING PRESCRIPTIONS

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ABSTRACT

We evaluated potential interactions of stand type, harvesting method, and equipment in an experiment using interactive simulation. We examined three felling methods (chain saw, feller-buncher, harvester) and two extraction methods (grapple skidder and forwarder) performing clearcuts, shelterwood cuts, and single-tree selection cuts in both an uneven-aged natural stand and an even-aged planted stand. Elemental time, distance traveled, travel intensity, and hourly productivity were estimated for each combination of stand type, harvesting method, and equipment. This technique provides a useful tool for comparing alternative systems in a range of harvesting situations.

Forest managers must consider the interactions of stand, harvest, and machine factors when selecting effective harvesting systems. These decisions are often difficult given the range of equipment available and the desire to use new harvesting schemes without field data on such interactions. Factors such as the tree size removed, initial and residual stand density, harvesting prescription, equipment dimensions, and operation methods can each affect the production and cost of a system.

Many researchers (20,21,25,32-34) have reported on the productivity and profitability of individual harvesting machines. The majority of these works addressed a single harvest method. Fewer reports are available that examined comparisons and interactions of harvesting systems (23,24,26,27). Such side-by-side field comparisons identify differences in harvesting systems. However, field studies are handicapped by the difficulty and/or cost of replicating experiments over a variety of conditions. In addition, some influencing factors such as bunch size are more difficult to control in the woods. Computer simulation combined with a limited amount of field data overcomes many of these shortcomings.

Many harvesting simulation programs have been developed since 1960. Goulet et al. (15-17) summarized the models available through 1980. Most of the models developed up to that time were deterministic, numerical simulation programs (1,5,29,36). The Harvesting Analysis Technique (31) was perhaps the most widely used of the programs in this category. None of the programs developed during this time period displayed results in graphical form or obtained user input in graphical form due to the computer hardware widely available at the time.

Since 1980, harvesting simulation programs have largely been developed on personal computer platforms and increasingly use graphical modes for both real time user input and reporting of results. Garbini et al. (14) used numerical simulation with graphical animation to illustrate material movement and machine activities in continuous simulation of a log merchandiser. In another decision simulator application, graphical animation and numerical data were used to make log bucking decisions (28). Fridley et al. (11,13) and Fridley and Jorgensen (10) reported the use of graphical interactive simulation for studying the design of swing-to-tree feller-bunchers used for thinning. Their program was used to identify the effect of various design parameters on feller-buncher performance during thinning (12). An interactive simulation program for modeling feller-bunchers was developed by Greene and Lanford (18,19) to examine the effects of stand and operating factors on the productivity of a small feller-buncher in second thinning operations. They also found variability between simulation operators but it did not appear to affect the utility of interactive simulation (22). Block and Fridley (3) described a three-dimen-

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† Forest Products Society Member.
Forest Prod. J. 48(9):81-86.

[illegible] interactive, real-[illegible] com-puter graphics simulation of a feller-buncher. The program allowed the user to vary physical parameters of the feller-buncher that would affect its performance in the woods. Baumgras et al. (2) presented a simulation model to estimate stump-to-truck production rates and multiproduct yields for conventional ground-based timber harvesting systems in Appalachian hardwood stands. A method of estimating tree damage was also addressed in conjunction with an interactive machine simulation program that could model harvesting performance in a variety of silvicultural operations (6).

Objectives

Our study used interactive computer simulation in a designed experiment to identify and evaluate the interactions of stand conditions, harvest prescriptions, and harvesting machines on the productivity and site impacts of harvesting alternatives. We specifically examined:

1. Distance traveled per harvested tree, time per tree, and felling productivity as affected by tree size and volume per acre felled, harvest method, and felling machine type;
2. Extraction distances, times and volumes per cycle, and extraction productivity as affected by bunch size, volume per acre extracted, harvest method, and the felling and extraction machine;
3. Travel intensity on the harvested site as affected by stand, harvest method, and machine;
4. Relative measures of system productivity as affected by the factors just mentioned.

Methods and Materials

Data from an intensive experiment using interactive simulation were used to examine the interactions just listed. The interactive computer simulation program used in the experiment was developed by Wang and Greene (35). Three harvesting systems (chain saw felling and grapple skidder, feller-buncher and grapple skidder, and harvester and forwarder) were simulated while performing felling and extracting activities in clearcut, single-tree selection, and shelterwood prescriptions. Felling was simulated on a 0.4-acre (132 ft. by 132 ft.) square plot. Skidding or forwarding simulations were performed on a larger area (19.6 acres) created by replicating the felling plot 49 times. A simulation was performed using a mouse to move the machine image in [illegible] site for extraction. The activities [illegible] machines were recorded and stored for later analysis. Data from the simulation experiments were analyzed statistically to examine the quantitative and qualitative differences among the interactions of stand, harvest prescription, and harvesting system. Differences in mean values of the variables examined were detected by Duncan's Multiple-Range Test at the 5 percent alpha level.

Four travel intensity categories of extraction travel were used to record the travel intensity (TI) within each felling grid and the proportion of each category on a harvested site (7):

TI1: Trees on the plot have been felled.

TI2: Trees that stood on the plot have been removed and no other traffic has passed through the plot.

TI3: Trees that stood on the plot have been removed and trees outside the plot have been skidded through the plot. Passes with a loaded machine are between 3 and 10.

TI4: More than 10 loaded machine passes have been made through the plot.

An even-aged planted stand and an uneven-aged natural stand of southern pine were used in experiments with the interactive simulation program. The conditions used to generate these two stands were as follows:

Planted stand

- even-aged
- loblolly pine
- stand density: 400 trees/acre
- stand age: 25 years
- dominant height: 60 feet
- uniform spatial pattern

Natural stand

- uneven-aged
- loblolly pine
- stand density: 250 trees/acre
- q-ratio: 1.3
- maximum height in maximum DBH class: 60 feet
- random spatial pattern

A Weibull distribution was used as the form of DBH distribution of planted stands (4) while the exponential function was used to characterize the reverse J-shape DBH distributions for natural stands (9,30). Applicable volume equations were used to determine individual [illegible] of trees for two generated stands are presented to show their structures.

Experimental Factors

To better understand and effectively use the interactive simulation program, a controlled experiment was designed. To reduce the operator learning effects, the experimental order of a simulation run was randomly arranged. The experiments were made by one operator who had significant practice before the experiment began. Factors considered in the felling experiment consisted of stand conditions (natural or planted), harvest methods (clearcut, shelterwood, or selection), and felling machines (chain saw, feller-buncher, or harvester). These 18 independent felling simulation combinations were each replicated 3 times, resulting in a total of 54 felling simulation runs. Single-tree selection left 165 trees per acre in the residual stand while shelterwood cutting retained 75 trees per acre. The clearcut harvest removed all standing trees. Since the extraction site was a larger area (19.6 acres) that represented 49 replications of the felling plot, extraction was simulated only one time for each felling combination. One of the three felling simulations for each combination was randomly selected for use in the extraction simulation. The order in which felling and extraction combinations were simulated was randomly assigned to prevent any learning effects from biasing results.

Operating patterns of the harvesting systems can be described as follows. The felling machine was first located at one end of the plot and then moved parallel to a swath of trees. The feller-buncher worked in a strip 15 to 20 feet wide. A narrower swath (about 10 ft. wide) of trees was used with manual chain saw felling as the operator walked along the swath. The cut-to-length harvester moved in a relatively straight trail working in a strip 40 to 50 feet wide. Trees on either side of the machine and within boom reach were removed based on operator choice. When the machine reached the end of the swath, it turned around and cut other trees in the next swath, continuing until the plot was finished.

The extraction machine was first located at the landing. Landings were assumed to be in the middle grid at the bottom of the logging site. Grapple skid-

TABLE 1. — Means and significance levels of felling simulation variables.[a]

	Stand		Machine			Harvest		
	Natural	Planted	Chain saw	Feller-buncher	Harvester	Clearcut	Shelterwood	Single-tree selection
DBH removed (in.)	7.0	8.1	7.5	7.5	7.6	7.7	6.8	8.2
Harvest volume (cords per acre)	10.2	33.0	21.5	21.8	21.5	29.5	18.0	17.4
Distance traveled per harvested tree (ft.)	13.0 A	10.1 B	13.3 C	13.7 C	7.6 D	9.8 E	11.0 F	13.8 G
Time per tree (productive min.)	0.66 A	0.74 B	1.17 C	0.32 D	0.62 E	0.66 F	0.63 F	0.83 G
Productivity (cords per PMH)	7.0 A	11.0 B	4.2 C	15.0 D	8.0 E	10.0 F	7.9 G	9.1 H

[a] Means with the same capital letter in a row are not significantly different at the 5 percent level with Duncan's Multiple-Range Test.

ders adopted free-style extraction and moved linearly to tree bunches and directly back to the landing, except in the case of protecting residual trees. Forwarders followed the trail of the harvester and loaded the log piles on either side of the machine by using their booms.

RESULTS

FELLING SIMULATION

We performed 54 simulations of felling and recorded the mean DBH and volume per acre removed to measure changes in stand conditions. These two stand variables, along with machine type and harvest method, were treated as independent variables. These variables each significantly affected distance traveled per harvested tree, time per tree, and hourly productivity at the 5 percent confidence level (**Table 1**). In planted stands, distance traveled per tree was shorter, time per tree was greater, and volume per productive machine hour (PMH) was greater than in natural stands during felling operations. This was due to the higher stand density, larger DBH, and greater volume per acre removed in planted stands. The distance traveled per tree was significantly greater for felling with either chain saw or feller-buncher than with a harvester. The harvester reached trees by extending its boom instead of moving the machine. Manually felling a tree with a chain saw took more time than felling with a feller-buncher or felling and processing with a harvester. Felling productivity was greatest in clearcuts, but single-tree selection was more productive than shelterwood cuts due to the larger tree sizes removed.

Harvesters traveled an average of 5.4 feet per harvested tree in clearcuts compared to 12.6 feet per harvested tree for feller-bunchers (**Table 2**). In single-tree selection, the difference was not as great, with harvesters traveling 10.0 feet compared to 15.7 for feller-bunchers. This travel savings comes at the price of lower productivity. Feller-bunchers are fast, with per-tree cycle times about half of those for harvesters that also delimb and process wood. As a result, feller-bunchers fell about twice as much wood per PMH as a harvester can fell and process.

TABLE 2. — Operating variables affected by machine and harvest in felling simulations.[a]

Harvest	Chain saw	Feller-buncher	Harvester
	Ground travel distance per harvested tree (ft.)		
Clearcuts	11.4	12.6	5.4
Shelterwood	12.7	12.9	7.5
Single-tree selection	15.7	15.7	10.0
	Time per tree (min.)		
Clearcuts	1.09	0.29	0.58
Shelterwood	1.02	0.28	0.58
Single-tree selection	1.39	0.40	0.70
	Volume per PMH (cords)		
Clearcuts	4.63	16.74	8.71
Shelterwood	3.65	13.28	6.69
Single-tree selection	4.21	14.77	8.39

[a] Six simulations per cell.

EXTRACTION SIMULATION

The trees felled and bunched during felling simulations were extracted to the landing during simulated skidding or forwarding operations. When the small felling plot was replicated 49 times to create the larger skidding area, individual trees or bunches of trees became indistinguishable on the computer screen. For the sake of operational feasibility and efficiency of simulation, we assumed six trees per bunch for extraction following chain saw or harvester felling and three piles following the feller-buncher.

Mean extraction distance, volume per cycle, cycle time, volume per PMH, and travel intensity category were analyzed by machine and harvest types (**Table 3**). Cycle volume averaged 0.69 cords for the grapple skidder and 3.95 cords for the forwarder. Extraction distance averaged 965 feet for the forwarder and 541 feet for the skidder. Due to the longer distance and greater payload, the forwarder took 23.8 minutes per cycle compared to 7.73 minutes for the grapple skidder. The net effect was production of 10.08 cords per PMH for the forwarder versus 5.61 PMH for the skidder. Mean extraction distance was significantly longer in partial cuts than in clearcuts. Similarly, hourly production rates were highest in clearcuts and lower in partial cuts.

Extraction performance was also sensitive to harvest methods and harvest system (**Table 4**). Mean extraction distance increased sharply when moving to the partial cuts from clearcuts. Hourly production was consistently highest in clearcuts and lower in the partial cuts. Interestingly, shelterwood harvests resulted in lower hourly productivity than selection cuts due to the smaller tree size removed.

TABLE 3. — Means and significance levels of extraction simulation variables.[a]

	Stand		Felling machine			Harvest			Extraction machine	
	Natural	Planted	Chain saw	Feller-buncher	Harvester	Clearcut	Shelter-wood	Single-tree selection	Grapple skidder	Forwarder
Cycle volume (cords)	1.71 A	1.85 B	0.69 C	0.69 D	3.95 E	1.76 F	1.75 G	1.84 H	0.69 I	3.95 J
Mean extraction distance (ft.)	735 A	630 B	529 C	554 D	965 E	606 F	724 G	717 H	541 I	965 J
Cycle time (min.)	14.38 A	11.79 B	8.10 C	7.37 D	23.80 E	12.12 F	14.50 G	12.64 H	7.73 I	23.80 J
Volume/PMH (cords)	6.03 A	8.17 B	5.29 C	5.92 D	10.08 E	7.61 F	6.33 G	7.37 H	5.61 I	10.08 J
Travel intensity Level 2 (%)	33 A	23 B	32 C	31 C	21 D	25 E	33 F	26 E	31 G	21 H
Travel intensity Level 3 (%)	29 A	17 B	8 C	13 D	47 E	20 F	21 G	27 H	11 I	47 J
Travel intensity Level 4 (%)	38 A	60 B	60 C	56 D	32 E	55 F	46 G	47 H	58 I	32 J

[a] Means with the same capital letter in a row are not significantly different at the 5 percent level with Duncan's Multiple-Range Test.

TABLE 4. — Operating variables affected by machine and harvest in extraction.[a]

Harvest	Chain saw/ grapple skidder	Feller-buncher/ grapple skidder	Harvester/ forwarder
		Volume per turn (cords)	
Clearcuts	0.70	0.70	3.88
Shelterwood	0.65	0.71	3.89
Single-tree	0.73	0.70	4.08
		Average extraction distance (ft.)	
Clearcuts	487	489	843
Shelterwood	548	576	1,048
Single-tree	551	597	1,005
		Cycle time (min.)	
Clearcuts	7.42	6.68	22.28
Shelterwood	9.16	8.58	25.77
Single-tree	7.72	6.86	23.35
		Volume per PMH (cords)	
Clearcuts	5.81	6.51	10.51
Shelterwood	4.42	5.32	9.25
Single-tree	5.66	5.94	10.49

[a] Two simulations per cell.

TABLE 5. — Proportion of felling grids in each travel intensity category by machine and harvest after felling and extraction.[a]

Harvest	Travel intensity	Chain saw/ grapple skidder	Feller-buncher/ grapple skidder	Harvester/ forwarder
			(%)	
Clearcuts	TI1	0	0	0
	TI2	27	27	22
	TI3	6	10	43
	TI4	67	63	35
Shelterwood	TI1	0	0	0
	TI2	35	35	29
	TI3	7	11	45
	TI4	58	54	26
Single-tree selection	TI1	0	0	0
	TI2	35	30	14
	TI3	11	18	53
	TI4	54	52	33

[a] Using the system described by Carruth and Brown (7).

EXTRACTION TRAVEL INTENSITY

The proportion of travel intensity category was defined as the number of felling grids (0.4 acres each) in each travel intensity category over the total number of grids (7 × 7 felling grids, 19.6 acres) in a logging area. It was used to evaluate how machine and harvest method affect the travel intensity (**Table 5**). The travel intensity category 4 (TI4) was the level of most concern since it caused the most damage to the soil. No difference of travel intensity existed between skidding in chain saw and feller-buncher felling areas. About 50 percent of the logging site was in TI4 after skidding and 30 percent after forwarding. The proportion of TI4 for the forwarder was lower than that for the skidder since the forwarder's higher holding capacity resulted in fewer passes to extract logs. The areas of TI4 after forwarding were also smaller than that after skidding. Harvesting methods also affected the travel intensity. Since clearcut produced more bunches with higher cords per acre, the proportion of TI4 in the clearcutting area was higher than ones in single-tree selection and shelterwood cutting areas. Due to the smaller bunch size in shelterwood cutting area with lower cords per acre, the proportion of TI4 was lower in such a logging site. If a smaller grid size is used, the accuracy of travel intensity in each grid will be improved in the extraction plot. The proportion of TI4 will be decreased because the number of loaded machine passes in a larger grid is divided into several smaller numbers in the smaller grids.

TABLE 6. — System productivity comparisons.

	Chain saw/ grapple skidder	Feller-buncher/ grapple skidder	Harvester/ forwarder
	(cords per week)		
Clearcuts	140	435	244
Shelterwood	106	345	187
Single-tree	136	384	235

SYSTEM PRODUCTIVITY

The three harvesting systems were examined based on their production per week. Two chain saws and one skidder were used in the chain saw/skidder system, one feller-buncher and three skidders in the feller-buncher/skidder system, and one harvester and one forwarder in the harvester/forwarder system. A hydraulic loader was used to load trucks in the skidder systems. The data showed that felling was the limiting function in feller-buncher/skidder and harvester/forwarder systems. Skidding, however, was the limiting function in the chain saw/skidder system. System production in clearcuts was 140 cords per week for the chain saw/skidder system, 435 cords per week for the feller-buncher/skidder system, and 244 cords per week for the harvester/forwarder system (**Table 6**). The system productivity in single-tree selection was somewhat lower than in clearcuts. The systems were least productive in shelterwood cuts compared to the other two harvesting methods.

SUMMARY

Our simulation study found that felling, skidding, and forwarding were affected significantly by stand, harvest, and machine factors. Distance traveled per harvested tree mainly depended on stand density, harvest intensity, and felling machine type. It was inversely related to stand density and harvest intensity. This distance increased as harvest method varied from clearcuts, to shelterwood cuts, to single-tree selection. The most important factors in felling time per tree were mean DBH removed, harvesting intensity, and harvest method. Extraction was most affected by payload and distance. Partial cuts increased distance but compensated for this with larger trees removed, which increased payloads.

We find interactive simulation to be a useful method for evaluating complex factors affecting timber harvesting decisions. It allows complete control of equipment during harvest by the user of the program. Disadvantages are the time required to perform the simulations with intensive manual inputs and the large grid size used to monitor traffic intensity. Further work will explore greater use of traditional numerical simulation for the most labor intensive applications, such as modeling extraction and use of smaller, more realistic grid sizes to monitor traffic intensity.

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