Production economics of harvesting small-diameter hardwood stands in central Appalachia

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Abstract

Three harvesting systems of chainsaw/cable skidder, feller-buncher/grapple skidder, and harvester/forwarder were simulated in harvesting three hardwood stands 30 to 50 years old in central Appalachia. Stands were generated by using a 3D stand generator. Harvesting prescriptions included clearcut, shelterwood cut, selective cut, diameter limit cut, and crop tree release cut. The interactions among stands, harvest prescriptions, and harvesting systems were evaluated statistically in terms of production, cost, and traffic intensity. The weekly production of the chainsaw/cable skidder system was 5,773 ft^3 (163 m^3) with a unit cost of $38 per 100 cubic feet (cunit) ($13.4/$m^3$). The feller-buncher/grapple skidder and harvester/forwarder systems could produce 22,153 ft^3 (627 m^3), and 8,423 ft^3 (239 m^3) with the unit cost of $34.3/cunit ($12/m^3) and $46.8/cunit ($17/m^3), respectively. Results indicated that the feller-buncher/grapple skidder system was the most productive and cost-effective system for harvesting small-diameter hardwood stands in central Appalachia under the simulated harvesting prescriptions. Compared to harvesting mature stands, harvesting small-diameter hardwood stands was about 15 percent (felling) and 14 percent (extraction) less productive, and 29 percent (felling) and 13 percent (extraction) more expensive. Results should help planners, loggers, and foresters efficiently manage and utilize small-diameter materials in the region.

Harvesting small-diameter stands of high densities is of interest to forest products companies, loggers, and landowners in central Appalachia in order to reduce fuel loading and improve residual stand health and timber utilization. However, harvesting such stands is usually more labor intensive and not cost-effective due to the small piece size processed and the non-merchantable products harvested. LeVan-Green and Livingston (2001) reported that average cost for thinning small-diameter and underutilized material is approximately $70 per ton while traditional markets for thinned material can only pay approximately $25 per ton for energy and $35 per ton for chips. Additionally, the efficiency of harvesting equipment could be lowered and the residual stand might be potentially damaged while partial cutting or thinning small-diameter stands.

Productivity and economic feasibility of thinning or partial cutting has been studied by many researchers in different regions. Wagner et al. (2000) found that harvesting sawtimber of less than 9 inches diameter at breast height (DBH) could not cover harvest and delivery costs, and the removal of sawtimber of less than 7.5 inches DBH had a negative return in the western United States. Combining data from previous field studies, Hartsough et al. (2001) examined six harvesting systems and developed cost models to estimate the costs of harvesting small-diameter trees of natural stands in the interior Northwest. They indicated that the models could be appropriate for long-term stand management plans but the gaps in the data and differences in the study conditions might limit

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the accuracy and potential applications. Han et al. (2004) reported that forest harvesting systems, road accessibility, hauling distance to manufacturing facilities, and market price of thinning materials were the major factors affecting economic feasibility of small-wood harvesting and utilization. By computing tree volume and potential product recovery, they evaluated the economic feasibility of an integrated harvesting system for harvesting small-diameter trees in southwest Idaho and concluded that harvesting costs for small-diameter trees increased as tree size decreased.

There is an abundance of small-diameter and underutilized materials available for harvest in the central Appalachian hardwood region (Luppold et al. 2001). However, markets and potential utilization of these materials are traditionally limited in the region. In addition, steep and uneven topography contributes to difficult logging conditions (Egan 1999), which could dramatically increase the operating costs of removing non-merchantable, small-diameter trees and further discourage the utilization of small-diameter materials. Research on the interactions of stand conditions, machine attributes, and harvest prescriptions especially for harvesting small-diameter hardwood stands appears to be lacking in central Appalachia. Such a lack of information has resulted in management decisions being based on either experience or very limited field tests. It is necessary to match the equipment and harvesting techniques to specific harvesting prescriptions and examine the production economics of harvesting small-diameter hardwood stands in central Appalachia to improve the residual stand health and biomass utilization, and reduce the forest fuel loading. However, extensive field data collection is prohibitive due to the higher cost and varied operating environments of harvesting small-diameter hardwood stands in the region. Computer simulation has proven to be a suitable research tool for evaluating harvesting operations under a variety of stand, harvest, and machine conditions (Wang and Greene 1999, Hartsough et al. 2001). The objectives of this study were to 1) generate three Appalachian hardwood stands of 30, 40, and 50 years old; 2) perform felling and extraction operations on these three stands under different harvesting prescriptions using a computer simulation model; and 3) statistically evaluate the production/cost effectiveness of the alternative harvesting systems in small-diameter hardwood stands.

Material and methods

Stands

Three natural Appalachian hardwood stands of 30, 40, and 50 years old were generated with a 3D stand generator (Wang et al. 2002). Each stand was 1.0 acre in size with a random spatial pattern. Stand densities were 531, 376, and 290 trees per acre for 30-, 40-, and 50-year-old stands, respectively. DBH averaged 5.2, 6.6, and 8.3 inches while the average total height varied from 50, to 55, and to 56 feet for these three stands, respectively. Basal area per acre was 114, 133, and 178 ft^2, and volume per acre was 998, 1,790, and 3,206 ft^3, respectively. Sugar maple (31%), American basswood (11%), and sweet birch (10%) were the major species for the 30-year-old stand and accounted for 52 percent of the total number of trees. Sugar maple (31%), black cherry (25%), and American basswood (13%) accounted for 68 percent of the total trees generated for the 40-year-old stand. The major species for the 50-year-old stand included yellow-poplar (28%), red maple (16%), and black cherry (15%).

Harvesting systems

The following systems were chosen and examined in the simulation study to reflect average systems expected to be found in central Appalachia (Long 2003, Wang et al. 2005): 1) chainsaw (CS)/cable skidder (CD); 2) feller-buncher (FB)/grapple skidder (GD); 3) harvester (HV)/forwarder (FW). Functions that were modeled for each machine were as follows: chainsaw (walk to tree, acquire, cut, and top/delimb), cable skidder (travel empty, choke, travel loaded, and unchoke), feller-buncher (drive to tree, cut, drive to dump, and dump), grapple skidder (travel empty, grapple, travel loaded, and release), harvester (move, boom movement, cut, process, and dump), and forwarder (move to load, load, travel loaded, and unload) (Wang et al. 1998, Wang and Greene 1999, Long 2003).

Felling simulations were performed on a 1.0-acre plot, which was replicated 36 times and created a total of 36 acres of each stand for extraction simulations. The felling machine was first located at one end of the plot, and then it moved parallel to a swath of trees. When the end of the swath was reached, the machine turned back and started on the next nearest swath until all trees selected to be cut were felled (Wang and Greene 1999). For the extraction simulation, the landing was assumed to be the middle point at one side of the logging site, and the main skidding roads were located in the middle of the logging site for cable and grapple skidders. The forwarder followed the trails of the harvester. Four travel categories were used to monitor the traffic intensity (TI) levels of skidders and forwarder (Carruth and Brown 1996): 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 with 3 to 10 loaded machine passes), and TI4 (more than 10 loaded machine passes have been made through the plot).

Harvesting prescriptions

Five different harvesting methods were examined during the simulation study: clearcut (CC), shelterwood cut (SW), crop tree release cut (CT), diameter limit cut (DL), and selective cut (SC). The shelterwood and selective cuts removed 80 and 30 percent of basal area of the stands, respectively. The smaller trees were removed in favor of desirable shade-tolerant trees by the shelterwood cut, while the selective cut removed dominant and co-dominant trees to stimulate the growth of the trees of lower crown classes. The diameter limit cut removed all trees 12 inches DBH or larger. Taking stumpage price into consideration, the crop tree release cut also removed 80 percent of the basal area and released valuable species such as black cherry, red oak, walnut, and hard maple. The size, species, and location of the trees were all considered during crop tree selection.

Data analysis

A three-factor, full factorial design (3 × 3 × 5) was implemented for the experiment. The three factors were stand, machine, and harvest, as described previously. There were a total of 45 treatment combinations. Each combination was replicated 3 times for a total of 135 felling simulation experiments. Another 135 extraction simulations were conducted based on the felling results.

Data were analyzed using analysis of variance (ANOVA). The general linear model (GLM) for analyzing felling operations is as follows:

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

	Stand			Machine			Harvest				
	30	40	50	CS	FB	HV	CC	SW	CT	DL	SC
DBH removed (in)	8.9 C	10.9 B	13.6 A	11.5 A	11.5 A	11.3 A	7.7 C	7.2 D	7.2 D	15.7 B	18.1 A
Avg. total height (ft)	58 C	65 B	68 A	64 A	64 A	63 A	53 B	52 B	52 B	80 A	82 A
Volume per felled tree (ft^3)	5.8 C	12.6 B	26.1 A	14.9 A	14.9 A	14.7 A	5.9 C	4.1 D	4.2 D	22.7 B	37.0 A
Distance traveled per harvested tree (ft)	15.3 C	16.9 B	18.8 A	15.6 A	15.6 A	9.3 B	9.2 C	9.2 C	9.5 C	25.8 B	40.6 A
Time per tree (productive min)	2.7 C	3.2 B	4.0 A	6.3 A	1.4 C	2.2 B	0.9 C	1.0 C	1.0 C	5.2 B	8.3 A
Cycle time (min)	4.8 B	5.0 B	6.1 A	6.3 B	1.9 C	8.0 A	2.8 D	3.5 C	3.5 C	7.1 B	10.0 A
Productivity (ft^3/PMH)	249 C	427 B	697 A	289 C	923 A	324 B	540 A	377 C	388 C	478 C	505 B

[a]Values in the same row and group followed by a different capital letter are significantly different at the 5 percent level with Duncan's Multiple-Range Test.

Table 2. — Hourly production models for felling and extraction machines.

Machine	Model[a]	r^2	RMSE	F-value	p-value
Chainsaw	44.27 − 2.89DBH − 190/DBH + 0.69DBH^2 + 1045.85/DT	0.60	52.61	203.86	0.0001
Feller-buncher	775.59 − 10.7DBH − 103/DBH + 0.62DBH^2 − 79.63DT + 7429/DT + 1.03DT^2	0.71	24.12	753.71	0.0001
Harvester	−77.97 + 130.46DBH − 1054.36/DBH − 0.33DBH^2 − 0.65DT + 1949.74/DT	0.67	31.25	532.28	0.0001
Cable skidder	144.22 − 0.00001AED^2 + 1.60PL − 1087.54/PL − 0.0003PL^2	0.69	26.78	635.59	0.0001
Grapple skidder	505.88 − 0.00004AED^2 + 0.005PL^2	0.64	40.39	295.79	0.0001
Forwarder	831.29 − 0.00005AED^2 − 5.20PL + 0.009PL^2	0.75	19.62	739.27	0.0001

[a]DBH = diameter at breast height (in); DT = distance traveled between harvested trees (ft); AED = average extraction distance (ft); PL = payload size (ft^e); RMSE = root of mean square error; hourly production was in ft^3/PMH.

$$Y_{ijkl} = \mu + S_i + H_j + M_k + S_i * H_j + S_i * M_k + H_j * M_k + \varepsilon_{ijkl} \quad [1]$$

i = set of stands {1, 2, 3}
j = set of harvesting methods {1, 2, 3, 4, 5}
k = set of felling machines {1, 2, 3}
l = number of replications {1, 2, 3}

where Y_{ijkl} = response variable (time per tree, cycle time, and productivity); S_i, H_j, M_k = effects of the stand factor, the harvest method factor, and the felling machine factor, respectively; μ = overall mean of the response variable; ε_{ijkl} = error component that represents all uncontrolled variability.

The GLM for analyzing extraction operations is as follows:

$$Y_{ijklmn} = \mu + S_i + H_j + M_k + PL_l + AED_m + S_i * H_j + S_i * M_k + H_j * M_k + PL_l * AED_m + \varepsilon_{ijklmn} \quad [2]$$

i = set of stands {1, 2, 3}
j = set of harvesting methods {1, 2, 3, 4, 5}
k = set of extraction machines {1, 2, 3}
l = set of payload size {1, 2, 3}
m = set of average extraction distance {1, 2, 3}
n = number of replications {1, 2, 3}

where Y_{ijklmn} = response variable (extraction cycle time, productivity, and traffic intensities); S_i, H_j, M_k, PL_l, AED_m = effects of stand, harvest method, extraction machine, payload size, and average extraction distance, respectively; μ = overall mean of the response variable; ε_{ijklmn} = error component that represents all uncontrolled variability.

Results

Felling operations

Average DBH of felled trees varied from 7.2 to 18.1 inches, while average total height was between 52 and 82 feet (**Table 1**). Volume per felled tree ranged from 4.1 to 37.0 ft^3. Distance traveled between harvested trees ranged from 9.2 to 40.6 feet and differed significantly among stands, and between harvester and chainsaw or feller-buncher. Because a harvester usually cuts and processes several trees at one stop, it always presented the least ground travel distance and was about half the distance of feller-buncher or chainsaw felling.

Time per harvested tree was between 2.7 and 4.0 minutes depending on stand conditions, and varied from 1.4 minutes for feller-buncher felling to 6.3 minutes for chainsaw felling (**Table 1**). It differed significantly among stands (F = 88.62; df = 2,134; p = 0.0001) and felling machines (F = 260.36; df = 2,134; p = 0.0001). However, it was not significantly different among clearcut, shelterwood, and crop tree release cuts because these three harvest methods usually removed the trees of similar sizes. Felling cycle time varied from 1.9 to 10.0 minutes and differed significantly among felling machines (F = 2470.86; df = 2,134; p = 0.0001).

Felling productivity was significantly different among stands (F = 5828.57; df = 2,134; p = 0.0001) and among felling machines (F = 9135.05; df = 2,134; p = 0.0001) ranging from 289 ft^3 (8 m^3) per productive machine hour (PMH) of chainsaw felling to 923 ft^3/PMH (26 m^3/PMH) of feller-buncher felling (**Table 1**). Regression equations were developed to predict the hourly felling production rate (**Table 2**). It was found that the felling productivity increased as the tree size increased and decreased with the distance between harvested trees. The harvester was more sensitive to the tree size than the feller-buncher and the chainsaw. The feller-buncher consistently presented higher productivity than the chainsaw and the harvester.

Extraction operations

Turn payload varied from 142 ft^3 (4 m^3) for the cable skidder, to 151 ft^3 (4 m^3) for the grapple skidder, to 384 ft^3 (11 m^3) for the forwarder. The payload sizes were classified into three groups: 100 ft^3 (3 m^3) (<100 ft^3), 300 ft^3 (8 m^3) (100 to 300

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

	Cycle time	Productivity	TI1[b]	TI2	TI3	TI4
	(min)	(ft^3/PMH)	(%)			
Stand (yrs)						
30	18.4 A	299 C	65.5 A	16.3 A	15.6 B	2.6 C
40	17.3 B	395 B	62.8 B	12.2 B	18.7 A	6.3 B
50	17.2 B	521 A	61.0 C	10.9 C	18.6 A	9.6 A
Machine						
CD	16.0 B	259 C	85.5 A	2.0 C	6.0 C	6.5 B
GD	12.9 C	426 B	27.4 C	35.2 A	35.8 A	3.7 C
FW	24.4 A	530 A	76.4 B	4.2 B	11.1 B	8.3 A
Harvest						
CC	16.1 D	398 C	57.7 D	11.3 C	21.1 A	9.8 A
SW	18.0 B	334 D	59.6 C	14.1 A	20.2 A	6.7 B
CT	18.1 B	336 D	59.4 C	14.8 A	19.2 A	6.5 B
DL	16.8 C	450 B	63.4 B	13.7 B	16.9 B	6.0 C
SC	19.3 A	507 A	75.5 A	11.5 C	10.7 C	2.4 D
Avg. extraction distance (ft)						
900	14.2 C	266 C	66.7 B	8.7 B	16.4 B	8.2 A
1,100	16.6 B	341 B	51.9 C	18.9 A	23.5 A	5.7 B
1,300	22.4 A	608 A	74.5 A	8.3 B	11.3 C	5.9 B
Payload size (ft^3)						
100	14.8 C	264 C	62.2 C	11.6 A	16.1 A	9.7 A
300	14.9 B	479 B	72.3 B	7.4 B	13.9 B	6.4 B
400	23.3 A	543 A	79.9 A	7.3 C	7.2 C	5.6 C

[a]Values in the same column and group followed by a different capital letter are significantly different at the 5 percent level with Duncan's Multiple-Range Test.
[b]Traffic intensity level.

ft^3), and 400 ft^3 (11 m^3) (>300 ft^3) (**Table 3**). Similarly, the average extraction distances were classified into three groups: 900 ft (274 m) (<900 ft), 1,100 ft (335 m) (900 to 1,100 ft), and 1,300 ft (396 m) (>1,100 ft) (**Table 3**). The average extraction distance varied among stands, harvests, and machines. The forwarder resulted in a longer forwarding distance of 1,244 feet (379 m) ranging from 800 to 1,600 feet due to its larger payload. The skidding distances ranged from 600 (244 m) to 1,200 feet (488 m) with an average of 904 (276 m) and 966 feet (294 m) with the cable and grapple skidders, respectively.

Average extraction cycle time varied from 12.9 minutes for the grapple skidder to 24.4 minutes for the forwarder (**Table 3**). It differed significantly among extraction machines (F = 875.09; df = 2,134; p = 0.0001), and average extraction distance (F = 1502.95; df = 2,134; p = 0.0001).

Extraction productivity averaged 259 ft^3 (7 m^3), 426 ft^3 (12 m^3), and 530 ft^3 (15 m^3) per PMH for the cable skidder, grapple skidder, and forwarder, respectively (**Table 3**). It increased with payload size while decreasing with average extraction distance. It also differed significantly among stands (F = 694.07; df = 2,134; p = 0.0001), extraction machines (F = 2775.41; df = 2,134; p = 0.0001), average extraction distance (F = 45.97; df = 2,134; p = 0.0001), and payload sizes (F = 275.97; df = 2,134; p = 0.0001). Using the stepwise selection procedure, regression equations were developed for predicting the extraction productivity by machine (**Table 2**).

TI3 and TI4 traffic intensities are the major concern since they caused the most soil compaction. TI3 and TI4 varied from about 13 to 40 percent among stand, machine, and harvest (**Table 3**). The lowest level of TI3 and TI4 was achieved in the selective cut site because of the large piece size processed and less volume per acre removed with this method. However, the highest traffic intensity level of TI3 and TI4 was always presented in the clearcut site. Both TI3 and TI4 were significantly different among extraction machines (F = 34220; df = 2,134; p = 0.0001), and average extraction distance (F = 2851.35; df = 2,134; p = 0.0001).

Cost and system analysis

Cost estimates of the harvesting machines were calculated by using the machine rate method (Miyata 1980). Hourly cost of a representative chainsaw was $29/PMH in the region with a mechanical availability of 50 percent (Long 2003). The purchase prices were assumed to be $130,000 for a skidder and $200,000 for a forwarder. The feller-buncher and harvester were purchased at the price of $180,000 and $252,000, respectively. Economic life was assumed to be 4 years for the feller-buncher and harvester, and 5 years for extraction machines. Fuel consumption rate was at 2.0 gal/PMH for cable skidder and forwarder, and 3.5, 3.2, and 2.5 gal/PMH for feller-buncher, grapple skidder, and harvester, respectively. Lubricant consumption was at 1.2 gal/PMH for skidders and 1.5 gal/PMH for other machines. Unit costs for fuel and lubricants were assumed at $1.7/gal and $10.1/gal, respectively. Maintenance and repair was 90 percent of depreciation for skidders and 100 percent for other machines. Machine mechanical availability was at 70 percent for the feller-buncher and 65 percent for other machines. Interest, insurance, and tax were assumed to be 20 percent. Labor cost was $10/PMH plus 35 percent fringe benefits. Scheduled machine hours were assumed to be 2,000 hours per year.

The feller-buncher had an hourly cost of $99.5. Hourly costs were estimated at $80.2 and $82.2 for the cable and

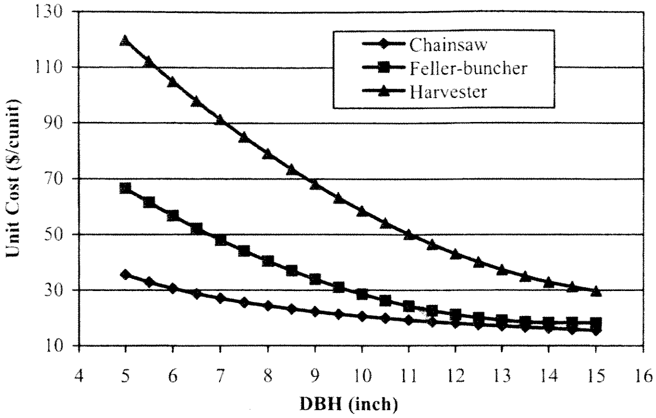

Figure 1. — Unit cost of felling operations.

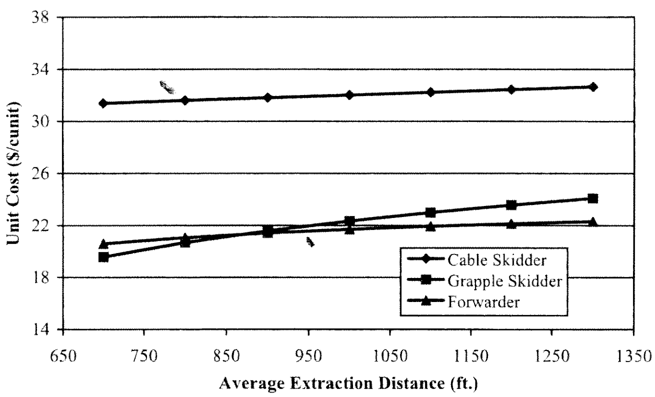

Figure 2. — Unit cost of extraction operations.

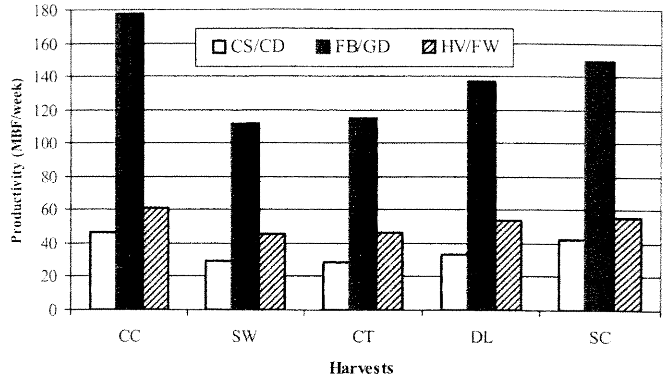

Figure 3. — Harvesting system productivity.

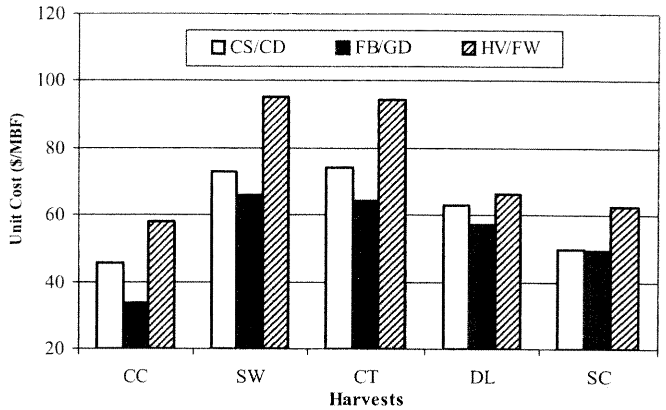

Figure 4. — Harvesting system unit cost.

grapple skidders. Operating the harvester and forwarder could cost $144.7/PMH and $112.9/PMH, respectively. The unit cost ($/cunit) for each individual machine was calculated by dividing machine hourly cost ($/PMH) with average hourly production rate (ft^3/PMH). It was estimated as $10.1/cunit ($3.5/m^3), $10.8/cunit ($3.8/m^3), and $44.7/cunit ($15.8/m^3) for the chainsaw, feller-buncher, and harvester, respectively. Operating the harvester was more expensive, about four times higher than feller-buncher or chainsaw felling. Unit felling cost decreased as tree size increased (**Fig. 1**).

Similarly, the unit cost for the cable skidder, grapple skidder, and forwarder was calculated as $31.2/cunit ($11.0/m^3), $19.3/cunit ($6.8/m^3), and $21.3/cunit ($7.5/m^3), respectively. Extraction unit cost was closely related to average extraction distance and payload size. It increased with an increase of the average extraction distance (**Fig. 2**). The cable skidder always presented a higher unit cost than the grapple skidder and forwarder. Operating the forwarder was about 8 percent more expensive than operating the grapple skidder when average extraction distance was less than 900 feet.

Three harvesting systems were balanced and compared in terms of the system production rate and unit cost. One chainsaw and one cable skidder were used for the chainsaw/cable skidder system (CS/CD), one feller-buncher and two grapple skidders were operated for the feller-buncher/grapple skidder system (FB/GD), and one harvester and one forwarder were employed in the harvester/forwarder system (HV/FW).

System productivity increased from the CS/CD system to the HV/FW system, and to the FB/GD system (**Fig. 3**). The weekly production rate for the CS/CD system was about 5,773 ft^3 (163 m^3) with a unit cost of $38.0/cunit ($13.4/m^3). The FB/GD system could produce 22,153 ft^3 (627 m^3) per week with a unit cost of $34.3/cunit ($12.1/m^3) while the HV/FW system's weekly production averaged 8,423 ft^3 (239 m^3) with the unit cost at $46.8/cunit ($16.5/m^3) (**Fig. 4**). Compared to the CS/CD and HV/FW systems, the FB/GD system was the most productive and least expensive. The consistently higher unit cost of the HV/FW system could be due largely to the smaller piece size processed and higher initial investment and maintenance fees.

System productivity decreased and unit cost increased from clearcut to selective cut and diameter limit cut, and to crop tree release and shelterwood cut. The productivity of a CS/CD system was 7,440 ft^3/week (211 m^3/week) with the unit cost of $28.4/cunit ($10.0/m^3) for the clearcut method, while system productivity decreased to 4,652 ft^3/week (132 m^3/week) with the unit cost of $45.4/cunit ($16.0/m^3) for the shelterwood cut method (**Figs. 3** and **4**). The unit cost for the HV/FW system was considerably higher than the other two systems for the shelterwood cut and crop tree release cut methods (**Fig. 4**). This indicated that the HV/FW system was expensive when dealing with smaller trees in partial cuts.

Discussion and conclusions

Felling production and cost were primarily affected by tree size removed, harvesting prescription, and type of felling machine. Compared with a chainsaw and feller-buncher, a harvester was more sensitive to individual tree size. The feller-buncher was the most cost-effective and productive felling machine. Clearcutting always resulted in the highest productivity while the shelterwood cut was the least productive method. The crop tree release cut removed smaller trees, which had almost the same silvicultural effects as the shelterwood cut but without sacrificing the stumpage price.

Extraction operation was mainly affected by payload size and average extraction distance. Due to its higher payload, a forwarder was the most productive machine with an hourly production of 530 ft^3 (15 m^3) that was about two times higher than that of a cable skidder. The relatively lower productivity of the cable skidder was partly due to the time consumed by choking, which accounted for about 25 percent of the total cycle time of the cable skidder.

Because of the smaller payload and more machine passes, the TI3 and TI4 level for both cable skidder and grapple skidder was up to 40 percent across the site for the clearcut method and still more than 20 percent with the other four harvest methods. However, TI3 and TI4 levels were consistently less than 20 percent across the site with a forwarder no matter what harvest method was used.

Harvesting small-diameter hardwood stands was apparently less productive and more expensive compared to harvesting mature stands in the central Appalachian region. The productivity of felling small-diameter stands was 20, 27, and 17 percent lower than felling mature or older stands with the chainsaw, feller-buncher, and harvester, respectively (Wang et al. 2004a, 2004b, 2005). Accordingly, the unit costs for felling small-diameter stands with a chainsaw, feller-buncher, and harvester were about 26, 34, and 28 percent more expensive than felling the older and mature hardwood stands by using the same machines. Extraction production rate in small-diameter stands was about 11, 17, and 13 percent lower than in older stands with a cable skidder, grapple skidder, and forwarder, respectively (Wang et al. 2004a, 2004b). The unit costs of the cable skidder and grapple skidder in small-diameter stands were about 15 and 20 percent more expensive in comparison with skidding in older and mature stands. The unit cost of a forwarder also increased 2.3 percent in small-diameter stands.

The feller-buncher/grapple skidder was the most productive and cost-effective system in harvesting small-diameter hardwood stands under the simulated harvesting prescriptions in central Appalachia. The terrain was indirectly modeled mathematically in this study, since the field time study data that were represented the terrain conditions in the region were used as input to the simulations were representative and spanned the conditions simulated in the paper. The simulated results are appropriate for the general terrain conditions in central Appalachia and can be used as guidance for managing small-diameter hardwood stands in the region and would be helpful for evaluating different harvest methods, prescriptions, and harvesting systems.

Some work, however, should be considered in a future related study. The operating cost for marking trees, which was mainly affected by basal area marked per acre (Sydor et al. 2004), could be included in the model since the cost of marking trees is especially noticeable in shelterwood and crop tree release cuts. Increased harvesting residue is another concern related to harvesting small-diameter stands. The potential fire risks related to harvesting small-diameter stands should be investigated. Additionally, a new module could be incorporated into the simulation model to evaluate the potential residual stand damage during harvesting. The simulation could be further refined by considering more detailed topography conditions.

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