

Productivity and cost of manual felling and cable skidding in central Appalachian hardwood forests

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Abstract

A field production study was conducted for a manual harvesting system using a chainsaw and cable skidder in a central Appalachian hardwood forest site. A partial cut was performed on a 50-acre tract with an average slope of 25 percent. Felling time per tree was most affected by diameter at breast height and the distance between harvested trees while skidding cycle time was mainly affected by turn payload size and skidding distance. Productivity of chainsaw felling was 362 ft.³ per productive machine hour (PMH) (2.23 thousand board feet [MBF]/PMH) with a unit cost of \$8.0/cunit (100 cubic feet) (\$13.0/MBF). Cable skidding productivity was 289 ft.³/PMH (1.78 MBF/PMH) and unit cost was \$27.0/cunit (\$50.0/MBF). The balanced manual harvesting system could produce 7,236 ft.³ per week (44.63 MBF/week) with unit cost of \$37.0/cunit (\$60.0/MBF).

Generally the more mechanized the harvesting system, the more productive it is. However, as mechanization of harvesting increases, operational costs also increase (Blinn et al. 1986). Mechanized harvesting also causes additional site disturbance and residual stand damage (Martin 1988). Due to the higher initial cost of mechanized harvesting machines, larger diameters and crowns of hardwoods, and the relatively steep terrain in central Appalachia, manual harvesting with chainsaw felling and a ground-based cable skidder is still the most commonly used system in the region.

Few previous studies addressed the production and cost of harvesting central Appalachian hardwood stands under

different machine and harvest prescriptions. Jones (1983) conducted a time study on a 60-acre tract with three thinning treatments in northern West Virginia. The three treatments were defined as 45 percent, 60 percent, and 75 percent of the residual stocking. The harvest comprised of manual felling with a

chainsaw and skidding with a cable skidder. Time studies showed that hourly felling production increased while skidding productivity decreased from the treatments 45 percent, to 60 percent, and to 75 percent of residual stocking. Regression equations were later developed based on the above time-study data (Brock et al. 1986), which can be used for estimating production rates and costs for similar thinning operations.

Howard (1987) took a different approach to estimating timber harvesting production and cost with cable skidders by collecting shift-level data on fuel consumption, repairs, maintenance, and other operating costs and combined that with telephone survey data. The model developed was based on these costs and previous detailed production studies to categorize the effect of timber size and species on logging costs and profitability. Howard found that tree size had the greatest effect on skid-

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ding costs and species only affected costs in felling. Howard stated that the results could be used to establish contract rates and merchantability rates based on stand characteristics.

Production analysis of thinning hardwood was conducted using small tractors instead of larger ground-based skidders (Huyler and LeDoux 1991). The productivity and cost of five small tractors were identified and compared using a computer program. The study reported that small-scale harvesting machines are feasible but type of machine, careful site selection, and layout are critical to ensuring a profitable operation. Compared to larger equipment, these small tractors were more suitable and economic in thinning of small stands with less soil compaction and less residual stand damage.

Some production/cost studies using manual harvesting systems have been conducted in harvesting planted pine stands in the south. Kluender and Stokes (1994, 1996) conducted a time study on a southern pine harvest consisting of manual felling, grapple skidding, and cable skidding. The harvest method ranged from clearcutting to single-tree selection and the proportion of basal area removed was used to measure harvest intensity. Lortz et al. (1997) conducted further analysis of southern pine felling with chainsaws and produced several equations for estimating felling times and productivity. Kluender et al. (1997) found that grapple skidders "were consistently faster and more productive than cable skidders." Their results also indicate that harvest intensity affects grapple skidding productivity but not cable skidding productivity. This was explained by the fact that the cable skidder had to approach every stem individually while the grapple skidder could grab several logs each time. The study found that grapple skidding productivity stayed the same, while cable skidding became more productive.

The objectives of this study were to:

1. conduct a continuous time study on manual harvesting systems with a chainsaw and a cable skidder in central Appalachian hardwood forest,
2. estimate the production rates and costs of chainsaw felling and cable skidder skidding, and
3. balance and examine the manual harvesting system rate and cost so as to compare it with other systems in the region.

Methods and data

The manual harvesting system examined consisted of felling with a chainsaw and skidding with a cable skidder. Felling was performed using a Husqvarna 372 chainsaw with 5.4-horsepower (hp) engine and bar length of 20 inches while skidding was done using a Timberjack 460 cable skidder with an engine of 174 hp. The field study was conducted from July to September of 2002 on Mead-Westvaco timberland in Randolph County, West Virginia. The site contained most hardwood species common to the central Appalachian region but was predominantly made up of six species: northern red oak (*Quercus rubra*), black birch (*Betula lenta*), red maple (*Acer rubrum*), sugar maple (*Acer saccharum*), American basswood (*Tilia americana*), and chestnut oak (*Quercus prinus*). The slope on this site ranged from 10 to 45 percent with an average of approximately 25 percent. The type of harvest on this site was a partial cut of marked trees. The initial stand density was about 250 trees per acre and the removal was 3.6 thousand board feet (MBF) per acre.

A handheld computer loaded with the Windows CE-based time study data logger was used to record elemental times and other harvesting related factors (Wang et al. 2003). When the handheld computer could not be used, times and operational variables were measured using a stopwatch and recorded on paper. A work cycle for each operation consisted of certain elemental functions and factors. The times for each function and the value of each factor were recorded in the field. Elemental time functions for chainsaw felling were defined as:

1. *Walk to tree*: Begins when the feller starts toward the tree to be cut. Ends when the feller reaches the tree.
2. *Acquire*: Begins when the feller starts clearing around the tree and judges where the tree will fall. Ends when the feller is ready to cut the tree.
3. *Cut*: Begins when the feller starts cutting the edge of the tree. Ends when the tree hits the ground.
4. *Top/delimb*: Begins when the feller starts delimbing the tree. Ends when the tree is finished and the feller starts toward the next tree to cut.

Harvesting factors or operational variables for chainsaw felling measured in the field include distance to tree (feet), tree species, diameter at breast height

(DBH) (inches), and merchantable height (feet). There was only one tree being cut per cycle for chainsaw felling. Order and location of felled trees were noted so that species, DBH, and merchantable height of the trees could be recorded when felling was complete.

Functions of the cable skidder were defined as:

1. *Travel empty*: Begins when the skidder leaves the landing with an empty cable. Ends when the skidder arrives at the felled stems to be extracted.
2. *Choke*: Begins when the skidder operator gets out to choke the felled stems. Ends when the skidder is full and ready to travel back to the landing.
3. *Travel loaded*: Begins when the skidder starts toward the landing full of felled stems. Ends when the skidder reaches the landing with the stems.
4. *Unchoke*: Begins when the skidder operator gets out to unchoke felled stems. Ends when the skidder leaves the landing for another load.

Stems were bucked with a bucksaw on the landing after skidding. The variables recorded for the cable skidder are travel distance from landing to stump (feet), number of felled stems per turn, tree species, butt diameter (inches), and merchantable length (feet) for each individual felled stem.

A total of 300 cycles for chainsaw felling and 150 cycles for cable skidding were observed in the field. The number of observations varied depending on the amount of time required collecting time study data. Each felled tree or stem skidded was measured for DBH/butt diameter to the nearest inch and merchantable height/length to the nearest one-half log or 8 feet. Local volume equations were used to compute the volume of felled trees or skidded stems (Wiant 1986, Rennie 1996).

Statistical Analysis Systems (SAS[®]) was used to analyze the data. The general linear model (GLM) was employed to determine if any differences of elemental times, cycle time, and hourly productivity existed among operational variables. The response variables were tested with Duncan Multiple Range Test at 0.05 level. Regression techniques were also employed to develop models for elemental times, cycle time, and productivity of chainsaw felling and cable skidder skidding.

Analysis and results

The GLM model for analyzing chain-saw felling is expressed as:

$$T_{ijklm} = \mu + D_i + H_j + S_k + DT_l + D_i \times H_j + D_i \times S_k + H_j \times S_k + D_i \times DT_l + \varepsilon_{ijklm}$$

$$i = 1, 2, \dots, 5$$

$$j = 1, 2, \dots, 6$$

$$k = 1, 2, \dots, 7$$

$$l = 1, 2, \dots, 7$$

$$m = 1, 2, \dots, n$$
[1]

where:

T_{ijklm} = m^{th} observation of the elemental times, cycle time, or hourly production,

μ = mean of each response variable,

D_i = effect of the i^{th} DBH,

H_j = effect of the j^{th} merchantable height,

S_k = effect of the k^{th} species,

DT_l = effect of the l^{th} level of distances between harvested trees,

ε_{ijklm} = an error component that represents uncontrolled variability, and

n = number of observations within each treatment.

Interactions among DBH, merchantable height, species, and distance between harvested trees were also considered in the model.

The GLM model for cable skidding is expressed as:

$$T_{ijklmn} = \mu + AD_i + AL_j + NL_k + TV_l + SD_m + AD_i \times AL_j + AD_i \times SD_m + AL_j \times SD_m + TV_l \times SD_m + NL_k \times SD_m + \varepsilon_{ijklmn}$$

$$i = 1, 2, \dots, 5$$

$$j = 1, 2, \dots, 6$$

$$k = 1, 2, 3, 4$$

$$l = 1, 2, \dots, 6$$

$$m = 1, 2, \dots, 6$$

$$n = 1, 2, \dots, p$$
[2]

where:

T_{ijklmn} = n^{th} observation of the elemental times, cycle time, or hourly production of cable skidding,

μ = mean of each response variable,

AD_i = effect of the i^{th} average butt diameter of felled stems per turn,

AL_j = effect of the j^{th} average merchantable length of felled stems per turn,

NL_k = effect of the k^{th} number of felled stems per turn,

TV_l = effect of the l^{th} turn payload,

SD_m = effect of the m^{th} skidding distance,

ε_{ijklmn} = an error component that represents uncontrolled variability, and

p = number of observations within each treatment.

Similarly, interactions among average butt diameter, average merchantable length, number of felled stems per turn, turn payload, and skidding distance were also considered in the model.

Elemental times and productivity Chainsaw felling

DBH of felled trees ranged from 8 to 26 inches and averaged 15.8 inches while merchantable height was between 8 and 56 feet with an average of 29 feet (Table 1). Distance between harvested trees varied from 2 to 110 feet with an average of 32.44 feet. Volume per felled tree ranged from 2.7 to 100.2 ft.³ and averaged 27.4 ft.³

Total felling time. — A felling cycle consists of elements walk to tree, acquire, cut, and top/delimb for each tree. Total felling time varied from 1.08 to 18.12 minutes with an average of 4.57 minutes (Table 1). It did not differ sig-

nificantly among species ($F = 1.90$; $df = 6, 288$; $p = 0.0810$) (Table 2). However, it did differ significantly among DBH classes ($F = 41.52$; $df = 4, 288$; $p = 0.0001$), merchantable height ($F = 4.20$; $df = 5, 288$; $p = 0.0011$), and distance between harvested trees ($F = 3.43$; $df = 6, 288$; $p = 0.0030$). A regression model was developed to estimate total felling time per tree (Table 3). The total felling time was best described by DBH and distance between harvested trees.

Walk to tree. — Time of walk to tree averaged 0.35 minutes and was between 0.03 and 1.75 minutes (Table 1). Since walk to tree is directly related to initial stand density and harvesting intensity, it was significantly different among distance between harvested trees ($F = 24.61$; $df = 6, 288$; $p = 0.0001$). However, there were no significant differences in walk to tree time among species ($F = 1.32$; $df = 6, 288$; $p = 0.2507$), merchantable length ($F = 1.10$; $df = 5, 288$; $p = 0.3630$), and DBH classes ($F = 1.92$; $df = 4, 288$; $p = 0.1077$) (Table 2).

Acquire. — There was no acquire time needed for some trees. However, a maximum of 6.27 minutes was taken to acquire for difficult trees (Table 1). No significant differences in mean acquire time were found among species ($F = 0.20$; $df = 6, 288$; $p = 0.9761$), DBH classes ($F = 1.96$; $df = 4, 288$; $p = 0.1020$), or merchantable height ($F = 0.58$; $df = 5, 288$; $p = 0.7160$) (Table 2).

Cut. — Time to cut a tree ranged from 0.28 to 4.55 minutes with an average of 1.57 minutes (Table 1). It was not significantly different among species ($F =$

Table 1. — Statistics of operational variables of chainsaw felling in the field study.

Variable	Mean	Standard deviation	Minimum	Maximum
Harvest conditions				
DBH (in.)	15.84	3.24	8.00	26.00
Merchantable height (ft.)	29.01	11.13	8.00	56.00
Volume per tree (ft. ³)	27.35	17.69	2.73	100.18
Distance between felled trees (ft.)	32.44	20.41	2.00	110.00
Elemental times (min.)				
Walk to tree	0.35	0.24	0.03	1.75
Acquire	0.40	0.62	0.00	6.27
Cut	1.57	0.82	0.28	4.55
Top/delimb	2.01	1.22	0.33	7.35
Delay	8.20	11.32	0.48	68.67
Total felling time ^a	4.57	2.14	1.08	18.12
Productivity (ft. ³ /PMH) ^b	362	182	59	1,227

^a Total felling time per tree does not include delays.

^b PMH = productive machine hour.

Table 2. — Means and significance levels of statistics for manual felling during time and motion studies.^a

	Elemental times (min.)						Productivity (ft. ³ /PMH) ^c
	Total felling time ^b	Walk to tree	Acquire	Cut	Top/delimb	Delay	
			Species				
Basswood	3.01A	0.19A	0.30A	1.08A	1.52A	0.34A	393BC
Red maple	3.70A	0.34B	0.29A	1.20AB	1.86AB	0.88A	291A
Birch	3.80AB	0.28AB	0.35A	1.44BC	1.73AB	1.23A	304A
Sugar maple	4.73C	0.37B	0.44A	1.68CD	2.24CD	0.37A	372BC
Chestnut oak	5.12C	0.32AB	0.59A	1.66C	2.55D	0.75A	477D
Red oak	5.48C	0.34B	0.47A	1.98D	2.69D	3.00A	423CD
Other	4.65BC	0.37B	0.40A	1.47BC	2.42CD	1.58A	353AB
DBH (in.)							
10	2.13A	0.17A	0.18A	0.70A	1.08A	1.92A	139A
15	3.41AB	0.32A	0.31A	1.10A	1.68AB	1.04A	269A
20	5.44BC	0.33A	0.50A	1.92B	2.69B	1.64A	441B
25	6.75C	0.43A	0.53A	2.68B	3.11B	3.73A	593B
30	9.85D	0.25A	0.10A	4.25C	5.25C	1.60A	610B
Merchantable height (ft.)							
8	2.61A	0.23A	0.22A	0.73A	1.43A	1.30A	114A
16	3.08A	0.29A	0.28A	0.97A	1.54AB	1.59A	208B
24	4.08B	0.30AB	0.31A	1.50B	1.96BC	0.98A	297C
32	4.86BC	0.32AB	0.45A	1.64B	2.39CD	0.78A	406D
40	5.27C	0.36AB	0.51A	1.93C	2.52D	3.52A	520E
48	9.65D	0.43B	0.56A	2.49D	3.47E	0.50A	535E
Distance between harvested trees (ft.)							
10	3.98A	0.11A	--	--	--	9.84A	325A
20	4.05A	0.19A	--	--	--	5.10A	352B
30	4.19AB	0.30B	--	--	--	5.36A	364B
40	5.49C	0.42C	--	--	--	13.48A	365B
50	4.90BC	0.46C	--	--	--	7.79A	370BC
60	4.93BC	0.57D	--	--	--	4.12A	372C
70	5.54C	0.75E	--	--	--	14.01A	374C

^a Means with the same letter in a group of a column are not significantly different at $\alpha = 0.05$ (ANOVA).

^b Total felling time does not include delays.

^c PMH = productive machine hour.

Table 3. — Models to estimate manual felling times and productivity.

	Models ^a	r ²	RMSE ^b	p-value	F-value
Cut time per tree (min.)	$0.1165 + 0.00555\text{DBH}^2$	0.52	0.57	0.0001	315.77
Top/delimb time per tree (min.)	$-1.1457 + 0.2117\text{DBH}$	0.32	1.01	0.0001	132.88
Total felling time per tree ^c (min.)	$-2.4295 + 0.4222\text{DBH} + 0.0002\text{DT}^2$	0.47	1.55	0.0001	128.89
Productivity (ft. ³ /PMH) ^d	$72.7178 + 0.881\text{DBH} \cdot \text{L} - 0.0003\text{DBH}^2 \cdot \text{L}^2 - 1.4087\text{DT}$	0.56	12.13	0.0001	122.43

^a DBH = diameter at breast height (in.); DT = distance between harvested trees (ft.); L = merchantable height (ft.).

^b RMSE = root of mean square error.

^c Total felling time per tree does not include delays.

^d PMH = productive machine hour.

1.92; $df = 6, 288; p = 0.0793$) (Table 2). However, cut time per tree was significantly different among DBH classes ($F = 64.25; df = 4, 288; p = 0.0001$) ranging

from 1.10 to 4.25 minutes and among merchantable height ($F = 4.42; df = 5, 288; p = 0.0007$) ranging from 0.73 to 2.49 minutes. A model developed using

regression analysis allows estimation of cut time per tree that was mainly affected by DBH (Table 3).

Top/delimb. — Top/delimb time per tree averaged 2.01 minutes and varied from 0.33 to 7.35 minutes (Table 1). Top/delimb time did not significantly differ among species ($F = 2.11; df = 6, 288; p = 0.0527$) with mean times ranging from 1.52 to 2.69 minutes. However, top/delimb times did differ significantly among DBH classes ($F = 24.48; df = 4, 288; p = 0.0001$) and among merchantable height ($F = 3.15; df = 5, 288; p = 0.0090$) with mean times ranging from 1.08 to 5.25 minutes and from 1.43 to 3.47 minutes, respectively (Table 2). A regression equation was produced to predict top/delimb time per tree (Table 3). The DBH was found to best predict top/delimb time per tree.

Delay. — A total of 54 delays were observed during manual chainsaw felling in the field study. Delay was usually due to maintenance of the saw and included filling it with gas and oil and sharpening the chain when dull. Manual felling delay ranged from 0.48 to 68.67 minutes (Table 1) and was not significantly different among species ($F = 0.81; df = 6, 288; p = 0.5663$), DBH classes ($F = 1.04; df = 4, 288; p = 0.3850$), merchantable height of trees ($F = 1.81; df = 5, 288; p = 0.1127$), or distance between harvested trees ($F = 1.21; df = 6, 288; p = 0.1211$) (Table 2).

Hourly productivity of manual chainsaw felling was between 59 (0.37) and 1,227 ft.³/productive machine hour [PMH] (7.57 MBF/PMH) with an average of 382 ft.³/PMH (2.36 MBF/PMH) (Table 1). It was significantly different among species ($F = 2.29; df = 6, 288; p = 0.0361$), DBH classes ($F = 59.62; df = 4, 288; p = 0.0001$), merchantable height ($F = 21.08; df = 5, 288; p = 0.0001$), and distance between harvested trees ($F = 3.44; df = 6, 288; p = 0.0030$) with ranges of 291 to 477 ft.³/PMH (1.80 to 2.94 MBF/PMH), 139 to 610 ft.³/PMH (0.86 to 3.76 MBF/PMH), 114 to 535 ft.³/PMH (0.70 to 3.30 MBF/PMH), and 325 to 374 ft.³/PMH (2.00 to 2.30 MBF/PMH), respectively (Table 2). A regression model was developed to estimate the hourly productivity of chainsaw felling (Table 3). Factors that affect the felling productivity are DBH, merchantable height, and distance between harvested trees.

Cable skidding

The number of felled stems skidded per turn ranged from 2 to 7 with an average of 4.5 stems per turn while volume per turn for cable skidding ranged from 29.2 to 170.7 ft.³ and averaged 104.2 ft.³ (Table 4). The skidding distance ranged from 50 to 4,000 feet with an average of 2,474.48 feet.

Skidding cycle time. — Time elements in a skidding cycle include travel empty, choke, travel loaded, and unchoke. The skidding cycle time averaged 21.75 minutes and varied from 5.80 to 29.56 minutes (Table 4). Mean skidding cycle time differed significantly among average butt diameter of felled stems per turn ($F = 19.57$; $df = 4, 139$; $p = 0.0001$), average merchantable length per turn ($F = 4.70$; $df = 5, 139$; $p = 0.0015$), number of felled stems per turn ($F = 8.26$; $df = 3, 139$; $p = 0.0002$), payload per turn ($F = 3.86$; $df = 5, 139$; $p = 0.0052$), and skidding distance ($F = 20.39$; $df = 5, 139$; $p = 0.0001$) with ranges of 19.91 to 25.34 minutes, 18.12 to 24.40 minutes, 21.14 to 22.87 minutes, 17.35 to 24.72 minutes, and 18.14 to 25.01 minutes, respectively (Table 5). Significant differences were also found in skidding cycle time among interactions between average diameter and average length, average diameter and skidding distance, average length and skidding distance, and number of felled stems and skidding distance. A regression model was developed to estimate skidding cycle time (Table 6). The skidding cycle time was best described by skidding distance and payload per turn.

Travel empty. — Travel empty time was between 0.22 and 9.73 minutes with an average of 5.71 minutes (Table 4). Mean travel empty time showed a significant difference among skidding distance levels ($F = 120.46$; $df = 5, 139$; $p = 0.0001$) (Table 5). A model developed using regression analysis allows estimation of travel empty time (Table 6). It was found that travel empty time was solely affected by skidding distance.

Choke. — Choke time varied from 2.25 to 11.17 minutes with an average 5.35 minutes per turn (Table 4). Mean choke time did not differ significantly among butt diameter classes ($F = 1.18$; $df = 4, 139$; $p = 0.3331$) with a range from 5.09 to 5.79 minutes. However, mean choke time was significantly different among merchantable length ($F = 5.85$; $df = 5, 139$; $p = 0.0003$), number of

Table 4. — Statistics of operational variables of cable skidding in the field study.

Variable	Mean	Standard deviation	Minimum	Maximum
Harvest conditions				
Average butt diameter of felled stems per turn (in.)	14.61	2.16	9.40	21.00
Average length of felled stem per turn (ft.)	30.67	6.57	18.00	48.00
Number of felled stems per turn	4.51	0.97	2.00	7.00
Turn payload (ft. ³)	104.18	31.20	29.24	170.70
Skidding distance (ft.)	2,474.48	864.01	50.00	4,000.00
Elemental times (min.)				
Travel empty	5.71	1.63	0.22	9.73
Choke	5.35	1.75	2.25	11.17
Travel loaded	7.52	1.84	1.12	11.52
Unchoke	3.17	0.92	1.12	5.52
Delay	4.24	2.65	0.83	10.62
Skidding cycle time ^a	21.75	3.71	5.80	29.56
Productivity (ft. ³ /PMH) ^b	289	76	80	472

^a Skidding cycle time per tree does not include delays.

^b PMH = productive machine hour.

felled stems per turn ($F = 8.05$; $df = 3, 139$; $p = 0.0002$), and turn payload ($F = 3.28$; $df = 5, 139$; $p = 0.0127$) with ranges of 4.15 to 5.87 minutes, 4.81 to 6.22 minutes, and 4.97 to 5.81 minutes, respectively (Table 5). A significant difference in choke time was also found among the interaction between average butt diameter and length.

Travel loaded. — Travel loaded time ranged from 1.12 to 11.52 minutes with an average of 7.52 minutes (Table 4). There were significant differences in travel loaded times among butt diameter classes ($F = 67.80$; $df = 4, 139$; $p = 0.0001$), merchantable length ($F = 38.65$; $df = 5, 139$; $p = 0.0001$), number of felled stems per turn ($F = 21.28$; $df = 3, 139$; $p = 0.0001$), turn payload ($F = 15.71$; $df = 5, 139$; $p = 0.0001$), and skidding distance ($F = 53.90$; $df = 5, 139$; $p = 0.0001$) (Table 5). Significant differences were also found in travel loaded time among interactions between average butt diameter and average length of stems per turn, average butt diameter and skidding distance, average length and skidding distance, turn payload and skidding distance, and number of felled stems and skidding distance. A regression model for estimation of travel loaded time was developed, and the travel loaded time was sensitive to skidding distance and turn payload (Table 6).

Unchoke. — Unchoke time was between 1.12 and 5.52 minutes and averaged 3.17 minutes (Table 4). It was sig-

nificantly affected by butt diameter ($F = 3.01$; $df = 4, 139$; $p = 0.0271$) ranging from 2.44 to 3.29 minutes, average merchantable length of felled stems per turn ($F = 2.98$; $df = 5, 139$; $p = 0.0203$) ranging from 2.75 to 3.39 minutes, and number of felled stems per turn ($F = 8.17$; $df = 3, 139$; $p = 0.0002$) ranging from 2.73 to 3.85 minutes (Table 5). However, turn payload did not significantly affect the unchoke time ($F = 1.43$; $df = 5, 139$; $p = 0.2192$). The interaction between average butt diameter and average length of stems per turn also significantly affected the unchoke time.

Delay. — Cable skidding delay was only observed 24 times during the field study. Skidding delay was usually due to maintenance of the skidder and fixing broken cable. Delay of the cable skidder ranged from 0.83 to 10.62 minutes with an average of 4.24 minutes (Table 4). It was not significantly affected by butt diameter ($F = 8.52$; $df = 4, 139$; $p = 0.0801$), average length of stems per turn ($F = 20.29$; $df = 5, 139$; $p = 0.2501$), number of stems per turn ($F = 7.37$; $df = 3, 139$; $p = 0.0904$), skidding distance ($F = 8.93$; $df = 5, 139$; $p = 0.3761$), and turn payload ($F = 1.52$; $df = 5, 139$; $p = 0.2027$) (Table 5). There was no significant difference in skidding delay among interactions between average butt diameter and average length of logs per turn, average butt diameter and skidding distance, average length and skidding distance, total volume and skidding dis-

Table 5. — Means and significance levels of statistics for cable skidding during time and motion studies.^a

	Elemental times (min.)						Productivity (ft. ³ /PMH) ^c
	Skidding cycle time ^b	Travel empty	Choke	Travel loaded	Unchoke	Delay	
Butt diameter class (in.)							
12	19.91A	--	5.79A	6.53A	3.13A	1.67A	236A
14	20.86A	--	5.31A	6.95A	3.29A	0.76AB	265AB
16	21.20A	--	5.09A	7.42A	3.13A	0.59AB	305BC
18	23.91B	--	5.49A	8.57B	3.19A	0.29B	327C
20	25.34B	--	5.55A	9.63C	2.44B	0.00B	332C
Average length of felled stems per turn (ft.)							
20	18.12A	--	4.15A	6.17A	3.07A	0.00A	195A
25	20.61B	--	5.87C	6.16A	3.28A	0.63A	224A
30	21.53B	--	5.66BC	7.18AB	3.25A	0.83A	280B
35	21.77B	--	5.02AB	7.90BC	3.05A	0.35A	317BC
40	24.40C	--	5.62BC	8.55C	3.39A	0.00A	328C
45	21.98B	--	4.47AB	8.87C	2.75A	2.77B	333C
Number of felled stems per turn							
3	21.62A	--	4.81A	7.54AB	2.73A	0.10A	268A
4	21.94AB	--	5.13AB	7.66B	3.09B	0.53A	273A
5	21.14A	--	5.47B	7.24A	3.15B	1.15B	303B
6	22.87B	--	6.22C	7.83B	3.85C	0.33A	324C
Volume per turn (ft. ³)							
60	17.35A	--	4.97A	5.31A	2.86A	0.74AB	209A
80	20.34B	--	5.58AB	6.45B	3.16AB	0.58AB	213A
100	21.02B	--	5.51AB	7.03C	3.30B	0.99B	270B
120	22.37C	--	5.28AB	7.92D	3.10AB	0.84B	303C
140	22.91C	--	5.81B	8.13D	3.17AB	0.27A	347D
160	24.72D	--	5.27AB	9.57E	3.22AB	0.43AB	373E
Skidding distance (ft.)							
1,500	18.14A	3.40A	--	5.32A	--	1.48A	300AB
2,000	20.93BC	5.25C	--	7.20C	--	0.51B	278BC
2,500	20.38B	4.75B	--	6.81B	--	0.72B	292AB
3,000	21.69C	5.86D	--	7.91D	--	1.55A	306A
3,500	23.75D	7.01E	--	8.33E	--	0.00C	266C
4,000	25.01E	7.59F	--	9.30F	--	0.00C	306A

^a Means with the same letter in a group of a column are not significantly different at $\alpha = 0.05$ (ANOVA).

^b Skidding cycle time does not include delays.

^c PMH = productive machine hour.

Table 6. — Models to estimate cable skidding times and productivity.

	Models ^a	r^2	RMSE ^b	p-value	F-value
Travel empty (min.)	$0.8461 + 0.0025SD - 0.0000002SD^2$	0.74	0.84	0.0001	191.03
Travel loaded (min.)	$0.5278 + 0.0027SD - 0.0000003SD^2 + 0.0256TV$	0.64	1.11	0.0001	81.92
Skidding cycle time ^c (min.)	$9.918 + 0.0049SD - 0.0000006SD^2 + 0.0338TV$	0.49	2.69	0.0001	42.74
Productivity (ft. ³ /PMH) ^d	$196.771 - 0.09SD + 0.00001SD^2 + 2.2425TV$	0.74	39.24	0.0001	129.57

^a SD = skidding distance in feet; TV = turn volume (ft.³).

^b RMSE = root of mean square root.

^c Skidding cycle time does not include delays.

^d PMH = productive machine hour.

tance, and number of felled stems and skidding distance.

Hourly productivity of cable skidding was between 80 ft.³/PMH (0.49 MBF/PMH) and 472 ft.³/PMH (2.91 MBF/PMH) and averaged 289 ft.³/PMH (1.78 MBF/PMH) (Table 4). It was significantly different among butt diameter classes ($F = 27.40$; $df = 4, 139$; $p = 0.0001$), average length of stems per turn ($F = 33.63$; $df = 5, 139$; $p = 0.0001$), number of felled stems per turn ($F = 31.16$; $df = 3, 139$; $p = 0.0001$), turn payload ($F = 7.69$; $df = 5, 139$; $p = 0.0001$), and skidding distance levels ($F = 13.40$; $df = 5, 139$; $p = 0.0001$) (Table 5). Significant differences were also found in hourly productivity among the interactions between average butt diameter and average length, average butt diameter and skidding distance, and number of felled stems per turn and skidding distance. A regression model was developed to estimate the hourly productivity of cable skidding (Table 6). Factors that affect cable skidding productivity are skidding distance and turn payload of the skidder.

Cost and harvesting system analysis

Estimates of hourly costs of chainsaw felling and cable skidding were computed using the machine rate method (Miyata 1980). A total of 2,000 hours per year were scheduled for the operations. Labor was \$10 per scheduled machine hour (SMH) plus 35 percent for fringe benefits.

The chainsaw used in manual felling cost \$600 and lasted approximately one year. After that time, no salvage value was expected. Mechanical availability of the chainsaw was assumed as 50 percent. Fixed cost was calculated to be \$0.60/PMH and operating cost was \$1.39/PMH. Labor cost was calculated at \$27.00/PMH. Total hourly cost for manual chainsaw felling was estimated to be \$28.99/PMH. Combination of the hourly cost with an average productivity of 362 ft.³/PMH (2.23 MBF/PMH) provided an estimated average unit cost of \$8.00/cunit (\$13.00/MBF) for manual chainsaw felling.

The cable skidder was purchased in 1999 for \$130,000. After an anticipated economic life of five years, salvage value would be \$25,040. Its mechanical availability was assumed as 65 percent and maintenance and repair charges were estimated at 50 percent of hourly

depreciation cost. Consumptions of fuel and lubricants were 3.5 gal/PMH and 1.0 gal/PMH at the rates of \$1.85/gal and \$4.65/gal, respectively. Fixed cost was calculated to be \$35.88/PMH and operating cost was \$22.57/PMH. Labor cost was calculated to be \$20.15/PMH. Total hourly cost of the cable skidder was estimated to be \$78.60/PMH. An average productivity of 289 ft.³/PMH (1.78 MBF/PMH) allowed an estimated average unit cost of \$27.00/cunit (\$44.16/MBF) for the cable skidder.

The system productivity and cost were examined based on the balanced manual harvesting system that consisted of one chainsaw and one cable skidder. The system costs included felling, topping/delimb, and skidding costs. Chainsaw felling was the limiting function in the system. The manual system could produce 7,236 ft.³ (44.63 MBF) per week at \$37.0/cunit (\$60.0/MBF).

Conclusions

Total felling time per tree was mostly affected by DBH of the tree being felled but was also affected by the distance between harvested trees. Cut and top/delimb times were most affected by DBH of the tree being harvested. Productivity of manual chainsaw felling was affected by the distance between harvested trees but was also affected by the interaction between DBH and merchantable height of the tree being harvested. An average productivity of 362 ft.³/PMH (2.23 MBF/PMH) or 181 ft.³/SMH (1.12 MBF/SMH) provided a weekly production of 7,236 ft.³ (44.63 MBF) with chainsaw felling. Its total hourly cost per PMH was \$28.99 (\$14.50/SMH).

Skidding cycle time and travel loaded time as well as cable skidding productivity were primarily affected by turn payload but skidding distance was another major factor that also influenced elemental times and productivity. Travel empty was solely affected by skidding distance. Hourly production for cable skidding was 289 ft.³/PMH (1.78 MBF/PMH) or 188 ft.³/SMH (1.16 MBF/SMH) with a weekly production of 7,524 ft.³ (46.41 MBF). Total hourly cost for the cable skidder was \$78.60/PMH (\$51.71/SMH).

Manual chainsaw felling was less productive than cable skidding and was the limiting function in the balanced manual harvesting system. This balanced manual harvesting system provided a weekly production of 7,236 ft.³ (44.63 MBF) with a unit cost of \$37.0/cunit (\$60.0/MBF) in harvesting typical central Appalachian hardwood stands. The results in this study can be used to compare the production and cost of other harvesting machines or systems used in the region and will be helpful for the loggers in selecting an appropriate system under certain stand and harvest circumstances.

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