TREE DIAMETER EFFECTSON COST AND PRODUCTIVITY OFCUT-TO-LENGTH SYSTEMS

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ABSTRACT

Currently, there is a lack of economic information concerning cut-to-length harvesting systems. This study examined and measured the different costs of operating cut-to-length logging equipment over a range of average stand diameters at breast height. Three different cut-to-length logging systems were examined in this study. Systems included: 1) felier-buncher/manual/forwarder; 2) feller-buncher/processor/forwarder; and 3) swing-to-tree harvester/forwarder. Operating costs were calculated by generating stands with the stand generator program PCWThin. Once stands were generated, costs for thinning were determined using a computer spreadsheet model known as the Auburn Harvester Analyzer. Each individual system followed different cost trends; however, for all systems, tree size had a significant effect on unit cost of wood produced. As tree size increased, unit cost of wood produced decreased. The swing-to-tree harvester system was much more expensive for small-diameter trees than the other two systems due to individual stem processing and small volume per tree but approached the unit costs of the other systems at larger tree sizes.

The objective of this study was to compare three cut-to-length logging systems that use different in-woods processing methods in order to examine the effects of harvested tree diameter on system productivity and cost per unit of wood produced. The machines used in the systems were: 1) feller-buncher/man-&/forwarder; 2) feller-buncher/processor/forwarder; and 3) swing-to-tree harvester/forwarder.

The feller-buncher/manual/forwarder method of harvesting consists of using a feller-buncher to fell and bunch trees followed by manual processing with chainsaws to remove limbs and buck the trees into desired lengths. All systems use a forwarder to transport logs from the stump area to set-out trailers.

The second cut-to-length system compared was the feller-buncher/processor/forwarder, which also uses a feller-buncher to fell and bunch the trees. However, once bunches are formed, a single mechanical processor delimbs, tops, and bucks the trees into a pile of logs ready for forwarding.

The third cut-to-length system, known as the swing-to-tree harvester/forwarder, uses one machine that performs both the felling and processing functions. A tree is severed and maneuvered to where it will be piled, similar to the way a feller-buncher operates. After the tree is in position, it is delimbed, topped, and bucked into merchantable lengths.

LITERATURE REVIEW

Cut-to-length systems can be either highly manual or mechanical. The forwarder, however, is the foundation of all cut-to-length systems. Forwarding is the process of transporting the wood from the stump to roadside with the load supported by the machine. Payloads for forwarders range from 16,000 to 36,000 pounds (5), while large skidders typically only pull around 1 cord (5,350 lb.) or less per cycle. Tufts et al. (19) found that the payloads of skidders ranged from 518 to 10,773 pounds; however, only 30 (7%) of the 4 16 observed cycles were heavier than 5,350 pounds. The large payload of a forwarder means it needs fewer passes over the ground to move the wood to the roadside (4). Fewer trips into the timber stand corresponds with decreased rutting and decreased soil compaction (10).

Forwarders offer more maneuverability, greater productivity, and less access area requirements than other systems (13). Tree-length systems require straight corridors in order to minimize damage to the residual trees. Forwarders, however, can meander through a stand of timber and do not require straight roads. Tbis is possible for two reasons. First, the material being transported is already bucked to a merchantable length, gener-

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TABLE — 1. Stands generated for selected cut-to-length systems using PCWThin.

Planting spacing	Site index[a]	Prior to thinning: Basal area	Trees per acre	Volume[b]	DBH[c]	Age	Thinning method: Stand entry no.	Pattern	Harvested portion: Basal area	Trees per acre	Volume	DBH	Residual stand: Basal area	Trees per acre	Volume	DBH
(ft.)		(ft.²/acre)		(cords)		(yr.)			(ft.²/acre)		(cords)		(ft.²/acre)		(cords)	
Systems: feller-buncher/manual/forwarder and swine-to-tree harvester/forwarder																
6 by 6	65	117.1	862	12.85	4.9	12		5th row/low	52.1	505	4.82	4.3	65.0	357	8.03	5.8
6 by 7	65	130.0	735	19.03	5.7	14		5th row/low	65.1	474	8.54	5.0	64.9	261	10.43	6.8
6 by 10	65	127.2	520	23.00	6.7	16		5th row/low	62.2	322	10.52	6.0	65.0	198	11.95	7.8
8 by 12	65	116.2	343	24.64	7.9	18		5th row/low	51.2	191	10.35	7.0	65.0	152	12.49	8.8
6 by 6	65	102.9	226	26.59	9.1	22	2	Low	37.9	109	9.35	8.0	65.0	117	17.24'	10.1
8 by 8	65	99.0	171	27.68	10.3	24	2	Low	34.0	76	9.17	9.1	65.0	95	18.51	11.2
8 by 8	65	99.6	147	30.44	11.2	27	2	Low	34.5	65	10.25	9.9	65.1	81	20.19	12.1
8 by 10	65	104.3	130	34.23	12.2	30	2	Low	40.0	62	12.84	10.9	64.9	68	21.64	13.2
System: feller-buncher/processor/forwarder																
6 by 6	65	117.1	881	12.85	4.9	12	1	9th row/low	52.1	529	4.78	4.3	65.0	352	8.07	5.8
6 by 7	65	123.0	655	18.26	5.7	14		9th row/low	57.9	398	7.79	5.2	65.0	257	10.42	6.8
6 by 10	65	127.2	520	23.00	6.7	16	1	9th row/low	62.3	324	10.49	5.9	64.9	196	12.51	7.8
8 by 12	65	116.2	343	24.64	7.9	18		9th row/low	51.3	192	10.34	7.0	65.0	151	14.30	8.9
6 by 6	65	102.9	221	26.67	9.1	22	2	Low	37.9	106	9.39	8.1	65.0	115	17.28	10.2
8 by 8	65	99.0	168	27.77	10.3	24	2	Low	34.0	75	9.21	9.1	65.0	93	18.55	11.3
8 by 8	65	99.6	145	30.48	11.2	27	2	Low	34.7	64	10.28	9.9	64.9	81	20.20	12.1
8by 10	65	104.3	127	34.24	12.2	30	2	Low	40.1	61	12.88	11.0	65.0	67	21.65	13.2

[a] Site index is base age of 25 years.
[b] AU volume is cords outside bark to a 3-inch top.
[c] DBH is quadratic mean diameter in inches.

ally under **20** feet, as compared to the tree-length system, which may have material over 40 feet in length. Second, the forwarder is articulated and is capable of turning around in a small area while carrying its payload.

Cut-to-length systems range from those that involve a considerable amount of manual labor to totally mechanized systems. When totally manual, trees are felled, delimbed, and bucked by chainsaw operators. Depending upon the final product, short bolts may be handpiled while higher valued and larger products, such as chip-n-saw Logs, are left where they are processed. After all processing is completed, a forwarder is then used to collect the merchantable material and load haul vehicles (5). A more mechanized approach uses a feller-buncher to fell the trees, yet chainsaw operators are still used to delimb and buck the wood.

Total mechanization of a cut-to-length system can be achieved by two methods. In the first system, a feller-buncher is used to fel! trees, a processor delimbs and bucks felled trees into logs, and a forwarder is used to transport the logs (3). Greene and Lanford (3) examined the use of a processor for thinning and concluded that tree utilization was greater than with chainsaw processing. 'The processor also added the benefit of increased safety, since all operations were mechanized. The slash from processed trees was deposited by the processor in the travel corridors where the limbs and tops acted as a bed for subsequent machine traffic.

The second totally mechanized cut-to-length system uses only two machines. A swing-to-tree harvester fells, delimbs, and bucks the wood (2,11,12). The processed wood is then transported by a forwarder. Of the two totally mechanized systems, the swing-to-tree harvester and forwarder combination has received the most attention (4,11,15,17). Two articles that appeared in *Timber Harvesting* (8,14) discussed both the advantages and disadvantages of the swing-to-tree harvester/forwarder systems compared to more conventional skidder systems.

Advantages included: 1) more economical on small tracts of timber; 2) less total labor cost, since only two employees are needed; 3) less fuel consumption by machines; 4) easier to merchandise highest valued products from trees; 5) lowest worker's compensation rates; 6) safe and comfortable work environment; and 7) minimal site and stand damage.

Disadvantages included: I) somewhat longer learning curve for operators; and 2) high initial cost of individual cut-to-length equipment.

METHODS

For this study, the thinning costs associated with three different cut-to-length machine combinations over a variety of harvested diameters were compared. A widely accepted measure of the average diameter at breast height (DBH) of the timber being harvested is the quadratic mean diameter of the removed wood. The quadratic mean DBH is a measure of the tree of average basal area. Harvested quadratic mean diameters were calculated with the following formula:

$$Q_d = [\text{basal area removed}/(\text{tree per acre removed} \times 0.005454)]^{.5}$$

The influence of eight different timber stands with harvested quadratic mean DBHs representing approximately 4, 5, 6, 7, 8, 9, IO, and 11 inches was used to compare the three cut-to-length logging systems. The computer growth and yield model PCWThin (1) generated all of the stands.

Harvesting patterns were chosen that matched the equipment and system being used. The feller-buncher/manual/forwarder and swing-to-tree harvester/forwarder systems used a fifth row pattern where 20 percent of the stand was clearcut and the remainder was thinned from below to the designated residual basal area of 65 ft.^{2}/acre. The feller-buncher/processor/forwarder system was capable of a ninth row pattern. One-ninth of the stand was clearcut and the remainder was thinned from below to the desired basal area.

The harvested quadratic mean diameters representing 4, 5, 6, and 7 inches were obtained from stands that were being row/low thinned for the first time. The remaining four quadratic mean diameters representing 8, 9, 10, and 11 inches were obtained from stands being thinned for the second time. A second thinning was necessary to obtain the larger diameters.

Table 1 contains a summary of the stand information used for all thinning patterns, as well as information concerning the harvested and residual stands. Based on advice from practitioners with considerable thinning experience, a target of harvesting 10 cords per acre for all diameter classes was established for both economical and silvicultural concerns. As shown in Table **1,** this target was attained for all diameters except for the 4- and 5-inch quadratic mean diameter classes.

After stands were generated, cost and productivity associated with thinning each stand was determined by using the Auburn Harvester Analyzer. This spreadsheet is capable of determining the productivity and unit cost for a tract of timber based on the type of logging system used, the size of timber being harvested, and other operation variables (18).

SISU Valmet cut-to-length equipment was used for system comparisons whenever possible due to the availability of published information. **Table 2** lists

TABLE 2. — Equipment specifications.

Valmet 503 feller-buncher
1 S-in. shear head
28-in. tires
Air conditioning
Suggested retail price: S 100,750.00
Valmet 546 Woodstar forwarder
28-in. front tires
700/50rear tires
650 Cranab loader with extension 22' 6" reach
Cranab 36-in. grapple with dampener
Joystick steering
Air/heat/light package
Headache rack
Suggested retail price: $ 176,310.00
Chainsaw and safety apparel
Husqvarna 272 chainsaw
20-in. Oregon bar and chain
Helmet system with eye and ear protection
Boots with calks
Protective pants
Protective gloves
High-visibility shirt
Tool carrier
First aid kit
Pulp hooks - 2
Holsters for hooks 2
Leather belt for tools
Lowers tape
Suggested retail price: S999 49
Valmet 546 Woodstar harvester & processor
942 Harvester Head (18 in.) or 940 Grapple Processor each with 998 telescopic boom
Air/heat/light package
28-in. front and 700/50 rear tires
Suggested retail price: $280,383.00

[a] Sources: Valmet Equipment: George Abray, Regional Sales Manager (Mobile, Ala.). Chainsaw and bar: King Power Equipment (Lafayette, Ala.). Safety apparel: Gransfor Bruks, Inc. (Summerville, S.C.). Suggested retail prices as of January 1995.

TABLE 3. — Production equations.

Machine		source
Feller-buncher	Shear= 0.1383+0.003×(DBH^2 - 72.25)	(16)
	Travel-to-tree = -0.1493+0.9889×Ln(ResBA)	
	Travel-to-dump = 0.0606+0.0322×volt	
	Dump = 0.0569+0.0 162×volt	
	Total + 0.1063+0.003×(DBH^2 - 72.25)+0.0889×Ln(ResBA)+0.0484×volt	
Chainsaw	Total = 0.0746+0.058×DBH - 1.028×branch+0.24796×DBH×branch	(6)
Forwarder	Loading = 0.028+0.3 1395(l/swing volume) Travel = 0.428+0.00155(distance)	(7)
Processor	Total = -0.341+0.1243×AvgDBH	(3)
Swing-to-tree harvester	Total = 0.223+0.0536(DBH)	(7)

where:
DBH = diameter at breast height (in.)
ResBA = residual basal area (ft.*)
Volt = volume per tree (ft." outside bark)
Branch = proportion of merchantable bole with limbs
Swing volume = average volume grappled by the forwarder (ft." outside bark)
Distance = average forwarding distance (ft.)
AvgDBH = average diameter at breast height of the harvested wood (in.)

TABLE 4. — Costs and work condition assumptions.

General information	
Hours/day	9
Days/week	5
Weeks/year	46
Tract size	SO acres
Average forwarding distance	990 ft.
Move-to-tract	4 hr.
Distance home	35 mi.
Quota	No quota
Support	
Pickups	1 @ S.45/mi.
Foreman	$2,000/mo.
Overhead	$2,000/mo.
Extra saws	
Manual system	2 @ S680
Processor system	1 @ S750
Harvester system	1 @ S750
Roads	
Push-out	0
Entrances	0
Landings	0
Machine operators	
Labor	$10.00/hr.
Fringe	40%
Equipment costs	
Spare chainsaw	Depreciation = 1 yr
Chainsaw and apparel	Depreciation = 1 yr.
Feller-buncher	Depreciation = 4 yr.
Processor	Depreciation = 5 yr.
Harvester	Depreciation = 5 yr.
Forwarders	Depreciation = 5 yr.
Interest	15%
Salvage value	20%

the equipment used, the options selected, and purchase prices. The equipment used for the feller-buncher/manual/forwarder system included Valmet 503 feller-bunchers, Husqvama 272 chainsaws and safety apparel, and Valmet 546 Woodstar forwarders. The feller-buncher/processor/forwarder system utilized Valmet 503 feller-bunchers, Valmet 546 Woodstar processors, and Valmet 546 Woodstar forwarders. The swing-to-tree harvester/forwarder system included Valmet 546 Woodstar harvesters and Valmet 546 Woodstar forwarders. Table 3 contains a listing of all production equations used and their source documents.

The Auburn Harvester Analyzer calculates the productivity and cost of the entire system. In addition, the utilization of each function is determined by combining machines in the system. By balancing the system to the least productive function, a utilization rate for each function is determined. Cost per cord for each function is obtained by combining hourly machine rates (9) with utilization and system productivity. Finally, the cost of the different functions are combined and the cost for on-board set-out trailers per cord for the system are calculated.

Three different Auburn Harvester Analyzer spreadsheets representing the three cut-to-length systems were developed for this project. All spreadsheets used identical information except for the machine types and the productivity of the different machines. Assumptions such as tract size, load size, taxes, and insurance rates were all identical. **Table 4** lists all the variables and values used to represent each system variable.

RESULTS

The Auburn Harvester Analyzer combined the stock and stand tables generated by PCWThin, system variables, machine rates, and the production equations to generate estimates of on-board cost for each cut-to-length system. **Table 5** is a summary of the on-board cost for each diameter class within each system, as well as a listing of weekly production and the balance of machines needed in each system to minimize cost. It should be noted that the on-board cost is the amount needed to pay all expenses, profit for the owner is not included. **Figure 1** is a graphical comparison of the different cut-to-length systems and allows the user to interpolate cost on all harvest diameters within the range examined. As **Figure 1** indicates, harvesting cost per cord is highly influenced by tree size for all systems examined. Small trees are very expensive to harvest.

The results from the feller-buncher/manual/forwarder system showed that manual processing required two to four chainsaw operators per feller-buncher. As the harvested trees increased in size, the felling and manual processing became more productive, which required more forwarding capacity. To achieve the lowest system costs, machines were balanced; that is, adequate machines were used in each phase of operation to keep each machine utilized as much as possible. On-board cost decreased as tree diameter increased. Production averaged approximately 50 cords per day per forwarder for all diameters of wood except the 4-inch class.

The feller-buncher/processor/forwarder system follows the same trends as the feller-buncher/manual/forwarder system. In the 4- and S-inch diameters, more felling capacity is needed to balance the mechanical processing. As the trees become larger, more forwarders are needed to balance the system. On-board costs are very similar to the manual system; however, they are slightly higher for all diameters except in the 4-inch class. Production for the feller-buncher/processor/forwarder system averages slightly over 50 cords per day per forwarder.

The swing-to-tree harvester/forwarder system required considerably more harvesting capacity in small-diameter wood with the swing-to-tree harvester, while more forwarding capability is needed in 10- and 11-i&wood. On-board costs per cord were considerably higher in the smaller diameters, but become comparable for tree sizes larger than 8 inches. Production for this system is slightly over 40 cords per day per forwarder.

CONCLUSIONS

Three cut-to-length thinning systems were compared in this study. Eight different stands were created by the stand generator PCWThin using fifth row/low and ninth row/low thinning patterns. Harvesting costs and productivity for each stand and system combination were calculated with the Auburn Harvester Analyzer spreadsheet. Tree size had a significant effect on unit cost of wood produced. As tree size increased, unit cost of wood produced decreased.

FELLER-BUNCHER/MANUAL/ FORWARDER SYSTEM

In general, the feller-buncher/manual/forwarder system had the lowest unit cost Of all the cut-to-length systems. Labor requirements are higher for this system. Four to six chainsaw operators are needed to balance with one feller-buncher and one to three forwarders, depending on the diameter of wood being harvested. Manual processing with chainsaws increases the chance for accidents and the potential for workers to experience physical stress and could contribute to worker turnover. Slash that remains with the logs creates downstream problems during loading and hauling.

FELLER-BUNCHER/PROCESSOR/ FORWARDER SYSTEM

The feller-buncher/processor/forwarder system had cost and production very similar to the manual processing system. For first thinnings, which typically have cut trees averaging 5 to 7 inches, this system offers the most potential. By having all operators in enclosed cabs, the system puts workers in a safe and comfortable work environment. Slash is separated from the merchantable logs and placed as a mat for machine traffic.

SWING-TO-TREE HARVESTER/FORWARDER SYSTEM

The swing-to-tree harvester/forwarder system had the highest unit cost of all the cut-to-length systems. Productivity was less than both the manual and processor systems. The swing-to-tree

TABLE 5. — On-board cost and productivity.

Feller-buncher/manual/forwarder system

DBH	No. of feller-bunchers	No. of chainsaws	No. of forwarders	Productivity (cords/wk.)	On-board costs (S/cord)
4	2	6	1	169	68. IS
5	2	6	1	252	45.15
6	1	4	1	242	33.51
7	2	6	2	547	24.76
S	2	5	2	545	23.17
9	2	6	3	823	19.34
10	2	6	3	845	IS.67
11	2	4	3	859	16.54

Feller-buncher/processor/forwarder system

DBH	No. of- feller-bunchers	No. of processors	No. of forwarders	Productivity (cords/wk.)	On-board costs (S/cord)
4	4	2	1	280	61.62
5	4	3	2	587	39.37
6	2	2	2	480	32.66
7	2	2	2	597	26.47
S	2	2	3	775	23.25
9	2	2	3	897	20.41
10	2	2	3	905	19.87
11	2	2	4	I.195	17.22

Swing-to-tree harvester/forwarder system

DBH	No. of harvesters	No. of forwarders	Productivity (cords/wk.)	On-board costs ($/cord)
4	4	1	149	113.78
5	3	1	195	68.94
6	2	1	214	46.92
7	2	1	242	39.82
8	1	1	233	25.75
9	1	1	231	28.07
10	1	2	368	23.60
				19.45

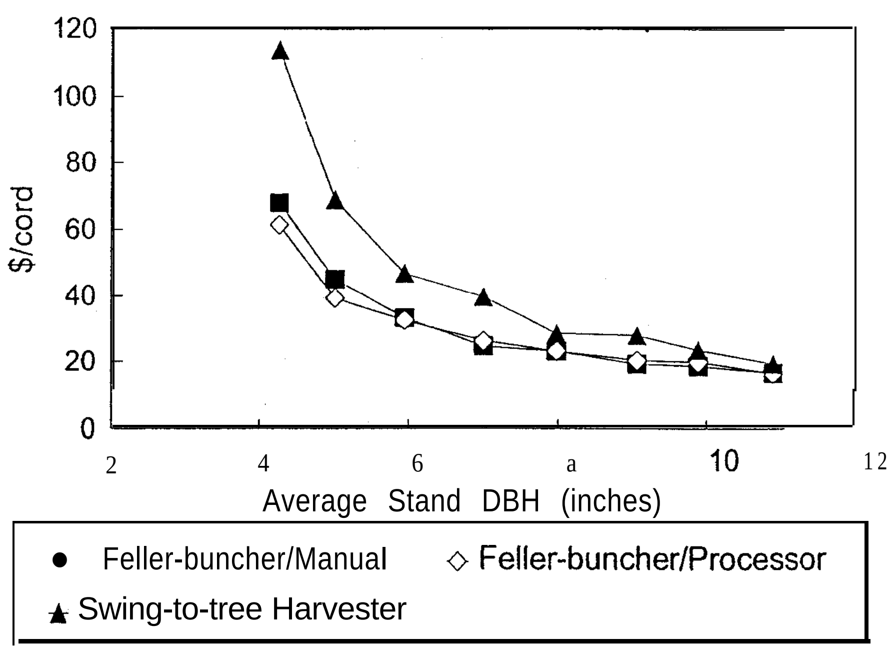

Figure 1. On-board cost comparison for cut-to-length systems.

harvester/forwarder system had the lowest labor requirements and consisted of only one operator for each of the two types of machines. The swing-to-tree harvester felled and processed individual trees. Although the swing-to-lrcc harvester/forwarder system had the highest initial cost, as tree size increased, the difference in unit costs for all systems decreased and was similar at the I I -inch class. If thinned trees had sawlog-grade material, the computerized measuring devices of the swing-to-kc harvester would be superior to the processing method of the other two systems studied. While both manual processing and mechanized processing have the ability to merchanciize plylogs and sawlogs from trees, the single-tree processing of the harvester probably measures more accurately. The swing-to-tree harvester/forwarder system would bc best used in second thinnings or other cuts where merchandising is important. In addition, swing-to-ircc harvesters have the added capabilities of working in steep, rocky, or swampy terrain. The reach of the boom allows the harvester to cover more ground than a machine that drives to each tree.

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