CUT-TO-LENGTH HARVESTING OF SHORT-ROTATION EUCALYPTUS

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ABSTRACT

Traditional whole-tree harvesting systems work well in short-rotation hardwood plantations, but other methods are needed where it is desirable to leave the residues on the site. We tested a system consisting of a cut-to-length harvester, forwarder, mobile chipper, and chip screen to clearcut a 7-year-old plantation of *Eucalyptus viminalis*. Three levels of debarking effort by the harvester (minimal, partial, and full), and two levels of screening (with and without) were evaluated. The harvester had the lowest production rate and highest cost of the system elements. Harvester production rate was strongly affected by tree size and somewhat by debarking level. Bark contents for full debarking averaged 1.5 percent; screening apparently did not reduce bark content any further. Estimated stump-to-truck costs (without screening) for the system in stands of good form varied from $19 per bone dry ton (BDT) for 11-inch DBH trees to $72/BDT for 3-inch trees. For trees in the 5- to 11-inch range, and an average forwarding distance of 500 feet, a balanced system would include three harvesters, two forwarders, and one chipper. The system may be cost competitive with whole-tree systems.

At present, most short-rotation woody crop harvesting in California, Oregon, and Washington is carried out by whole-tree systems that include feller/bunchers, skidders, chain flail delimber/debarker/chippers, and chip vans for hauling the clean chips to the pulp mill. Residues from the flail are usually comminuted on the site with a tub grinder or other device and hauled in chip vans to a powerplant. This system works very well when a viable fuel market exists for the residues.

When fuel prices do not cover the costs of comminution and transport, managers must decide whether to leave the residues on the site, and what system to use in this situation. One possibility is a cut-to-length (CTL) system consisting of a harvester and a forwarder. The harvester removes the branches and top at the stump, and cuts the tree to log lengths that may be selected by the operator. Residues are left distributed within the stand, which recycles nutrients and eliminates disposal costs. In Australia, New Zealand, and South Africa, harvesters have also been employed to debark eucalyptus stems. Wingate-Hill and MacArthur reported on three single-grip harvester heads that had been modified to debark eucalyptus (14). An Osa 762 had sharp bars added to the feed rollers and bars mounted on the frame to cut through and remove bark. In a short trial of thinning *E. regnans*, the harvester produced 10.4 m^3 per productive machine hour (PMH) with trees of 0.52 m^3 average volume. About 93 percent of the bark was removed. A Lako head mounted on a Kato excavator was modified by removing the delimbing knife belts and installing feed rollers surfaced with spiral bars. Over a number of trials on various sites and several species, the machine harvested between 32 and 101 trees per PMH. Debarking quality varied, with between 70 and 100 percent of the bark removed. A Waratah 240 HTH harvester was studied in thinning operations in Tasmania. When processing stringy-barked species averaging 0.44 m^3 per tree, the mean bark removal was 91 percent, and debarking, delimbing, and topping time per tree averaged 0.71 minutes per tree. In a New Zealand study, two similar Waratahs produced 31 tree-lengths per PMH when debarking and bucking decked trees averaging 0.82 m^3 (3). Howe (10) studied a Bell TH 120 harvester clearcutting a eucalyptus plantation in South Africa. He reported a production rate of 11.8 m^3 per scheduled hour for felling, debarking, and piling of 6-m logs on flat terrain for skyline yarding, with tree volume averaging about 0.24 m^3.

Although skidders could be used to transport delimbed and topped trees or log lengths, forwarders must be utilized to transport debarked logs, in order to avoid contamination by soil. Many forwarders are limited to carrying logs of about 20 feet or less in length. Forward-

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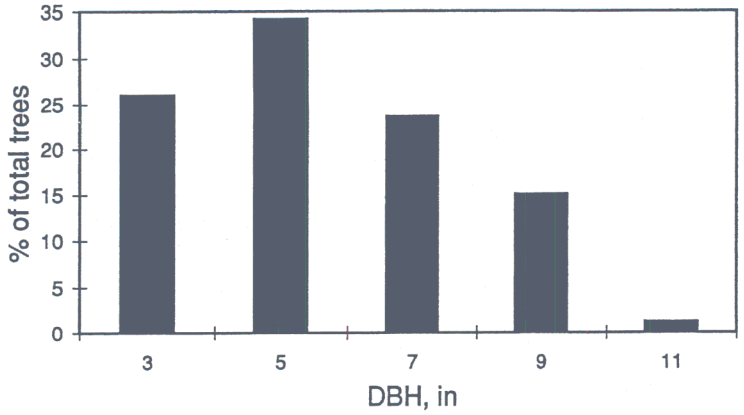

Figure 1. — Distribution of diameters of the harvested stems.

ers generally travel on the mat of slash left by the harvester, and therefore have the potential to create less soil compaction than do skidders. Compared with skidding, very little dust is produced while forwarding.

Possible disadvantages of the CTL system include higher site preparation costs due to the on-site residues, and higher harvesting costs. Although rankings vary from study to study, in many cases harvester-forwarder CTL systems have cost more than other systems operating under similar conditions. Holtzscher and Lanford (9) simulated three systems for thinning pine plantations; the two with feller/bunchers were cheaper than a system with a harvester. Lanford and Stokes (11) compared CTL and whole-tree systems for thinning young pine plantations. The whole-tree system was less expensive during the actual study, but projected costs were essentially identical for the two systems. Three studies by Gingras also compared CTL and whole-tree systems in eastern Canada. One (4) found CTL costs to be comparable or lower, in areas that required considerable travel between cut blocks. In contrast, the two other studies found the CTL systems to be 15 to 30 percent more expensive (5,6). Hartsough et al (7) found that stump-to-mill costs for a CTL system were about 25 percent higher than for a whole-tree system in a plantation, and 50 percent higher in a natural stand.

This study quantified the costs of a CTL system operating in eucalyptus, and the resulting bark content of chips from three levels of debarking intensity, with or without screening.

Approach

Stand

A 7-year-old stand of *Eucalyptus viminalis* at Simpson Fiber Farms (now Action Tree Farm) near Corning in northern California was chosen for the trial. Seedlings had been planted on an 8- by 10-foot spacing. A sample cruise prior to harvest indicated that 490 stems per acre remained, including forks below breast height and standing dead stems. Trees averaged 5.6 inches in diameter at breast height (DBH), 46 feet tall, and 3.3 $ft.^3$ volume inside bark.

The trees, grown from unimproved seed, were highly variable in diameter (**Fig. 1**), height, and form compared to more recent stands of clonal origin. Almost a quarter of the trees were forked, and many trees had crooks. A majority of the trees were leaning due to the prevailing wind, and 5 to 10 percent of the original trees were uprooted and leaning severely or on the ground. The uprooting was attributed to a high water table during the winter months. The terrain was flat, the soil surface was dry during the harvesting trial, and there was little or no undergrowth.

Equipment and Harvesting Operation

Western Power and Equipment of Bend, Oreg., supplied a Bell TH120 tracked harvester powered by a 112-Hp Cummins engine. The SP 550 dual-feed-roller harvester head was mounted on the end of a swing boom that had a reach of 13 feet. The head was modified to improve its debarking performance in eucalyptus by replacing the chain-equipped rubber-tired feed rollers with steel rollers equipped with spiral cutting edges. When the harvester head is used on eucalyptus in South Africa, the double-bevel lower delimbing knives are replaced by single-bevel knives to improve debarking, but the head supplied for the tests had the standard double-bevel knives. Western Power and Equipment also provided a Bell T12B 12-ton forwarder.

The equipment operator was well-skilled, with 8,000 hours of experience on various harvesters. He also ran the forwarder during the single load that we observed, and was skilled with the forwarder as well.

Harvesting and forwarding were conducted on July 21 to 23, 1997. The operator used the first day to familiarize himself with harvesting in the test stand. Time-motion studies were carried out during the second and third days.

The harvester clearcut the stand, using strips parallel to the 8-foot tree spacing direction. Three to four rows were cut per strip. Because of the down and leaning trees, logs were piled only on the side of the harvester opposite the uncut stand. Logs of up to 20 feet were cut if possible, although most were in the 16- to 18-foot range.

To investigate the debarking characteristics of the eucalyptus and resulting bark contents, three different specifications were followed by the harvester operator: "all" bark removed, "partial" debarking, and "standard" single-stroke delimbing with whatever debarking was accomplished. Removing all of the bark required between one and nine passes through the delimbing knives. (On forked or crooked trees, it was not possible to remove all of the bark.) For partial debarking, the operator used one to five strokes, with the goal of removing approximately half of the bark from each tree. On the first day of time-motion study, all the bark was removed. Half of the second day was devoted to the partial debarking specification, and half a day to standard processing.

The logs were forwarded to the roadside and decked for the chipping and screening that were carried out on July 28.

An experienced chipping contractor supplied a Morbark 20 chipper with knuckleboom loader. Initially, the chipper pulled logs from the cold decks, but a front-end loader was added to speed the feeding rate. Some of the logs were chipped directly into chip vans. Others were chipped into an Oregon Mill Service (OMS) Super Beaver portable chip

screening plant, and the screened chips were conveyed into vans. The screening plant included an infeed hopper, disc screen, fines screen and blower, rechipper for oversize material and an outfeed conveyer.

Data collection and analysis

Height and diameter measurements were taken on a sample of trees before harvesting, and volumes were calculated from proprietary diameter-height-volume relationships developed by Simpson Fiber Farms for their *E. viminalis*. Average log volume was calculated from total volume harvested and the total number of logs cut. Based on the Simpson data, we assumed a ratio of 32 bone dry pounds per cubic foot of bole wood under bark, and 45 percent moisture content (MC) (wet basis) for fresh material. For chip vans, we assumed 25 green tons net per load.

We conducted a time-motion study of the harvester and collected observations on over 300 stems, approximately a third of them under each debarking specification. The cycle for each stem was divided into the following elements: Move, Fell, Process, and Fork&Crook Delays. The latter were any times that could be specifically attributed to the two poor form characteristics. Brushing time was recorded separately. Brushing consisted of cutting nonmerchantable trees, including standing trees of less than 3 inches DBH and decayed dead and down trees. Some of the latter were up to 7 inches DBH. Any other delays were also recorded separately. Along with the times for each tree, we recorded move distance, DBH, and number of logs cut.

Only one forwarder load was observed. The forwarding cycle was separated into TravelEmpty, Load, TravelWithinStand while partially loaded, TravelLoaded to the roadside, and Unload which included decking.

The time-motion data for the harvester were statistically analyzed to estimate cycle time elements as functions of the stand characteristics and operating conditions. Since only one forwarder load was timed, forwarder relationships from another study (7) were adjusted to give element times that were close to those observed. For chipping, results from a study of chipping directly from cold decks of CTL logs was used (2).

Harvesting, forwarding, and chipping cycle times and production rates were then calculated over ranges of tree size and forwarding distance, for each of the three debarking specifications. Since estimates were desired for future stand conditions, i.e., for trees with better form, adjustments were made to the observed harvester productivity and forwarder load size. The adjusted production rates were combined with estimates of hourly costs for the harvester and forwarder, to give costs per bone dry ton (BDT).

Chip samples were taken from vans using the standard sampling apparatus at the pulpmill. The samples were analyzed for bark content, overs (2 in.), and fines (1/4 in.) by the Simpson chip evaluation lab.

TABLE 1. — Cycle time elements and associated variables.

	Mean	Standard deviation	Observations
Harvester			
Move (cmin/move)	12.1	9.1	198
Trees/move	1.71		
Fell (cmin/tree)	13.6	9.6	339
Process (cmin/tree)	38.4	24.7	339
Brush (cmin/tree)	9.2	23.2	340
Crook&ForkDelay (cmin/tree)	3.2	11.0	340
OtherHarvProductiveDelays (fraction of cycle time)	0.048		
Move distance (ft./move)	5.05	2.89	198
DBH (in.)	5.62	2.11	339
TreeVolume ($ft.^3$ (inside bark))	3.31		
Logs/tree	1.82	0.71	340
Forwarder			
Travel empty (min./load)	1.13		1
Load (min./load)	9.11	(14 swings)	1
Travel within stand (min./load)	3.44		1
Travel loaded (cmin/load)	1.44		1
Unload/deck (cmin/load)	5.17	(10 swings)	1
Travel empty dist (ft.)	130		1
Travel within stand dist (ft.)	140		1
Travel loaded dist (ft.)	200		1
Logs/load	106		1
Load size ($ft.^3$ (BDT))	193 (3.09)		1

TABLE 2. — Harvester productivity relationships.

Move, cmin/move = $6.09 + 1.189 \times$ Distance
$r^2 = 0.14$, $F = 33.$, $n = 198$

Fell, cmin/tree = $10.40 + 0.511 \times$ DBH
$r^2 = 0.02$, $F = 7.6$, $n = 338$

Process, cmin/tree = $15.75 + (0.333 + 0.166 \times \text{Partial} + 0.515 \times \text{Full}) \times \text{DBH}^2$
$r^2 = 0.57$, $F = 149.$, $n = 339$

Brush, cmin/tree = 9.24

Crook&ForkDelay, cmin/tree = $-3.12 + 1.125 \times$ DBH
$r^2 = 0.05$, $F = 17.$, $n = 340$

ProductiveTime, cmin/tree = (Move/TreesPerMove + Fell + Process + Brush + Crook&ForkDelay) × (1 + OtherHarvProductiveDelays)

LogsPerTree = $0.7 + 0.2 \times$ DBH

where:
Distance is in feet
DBH is in inches

Results and discussion

Cycle times and productivities

The time-motion data are summarized in **Table 1**. The harvester move distance was about 15 percent greater than calculated from theory, assuming straight, one-way travel and the observed 3.5 rows per strip. Theoretical distance is:

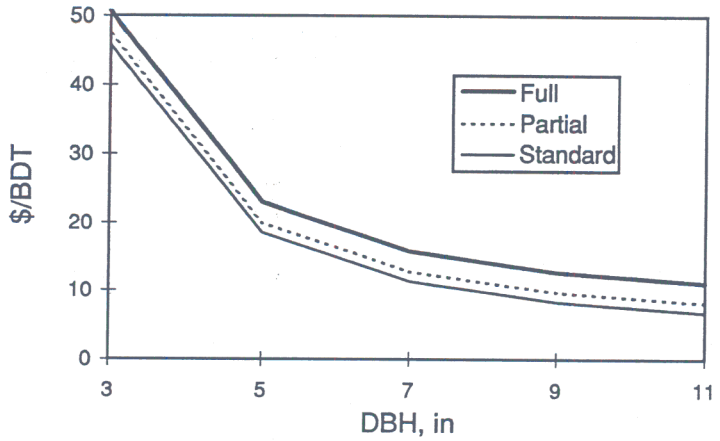

Figure 2. — Estimated harvester costs in stands of good quality, for various levels of debarking effort.

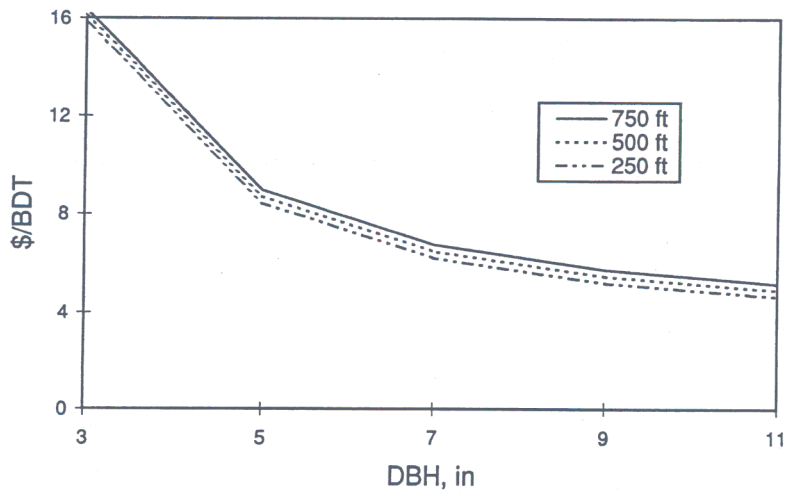

Figure 3. — Estimated forwarding costs in stands of good quality, for three different forwarding distances.

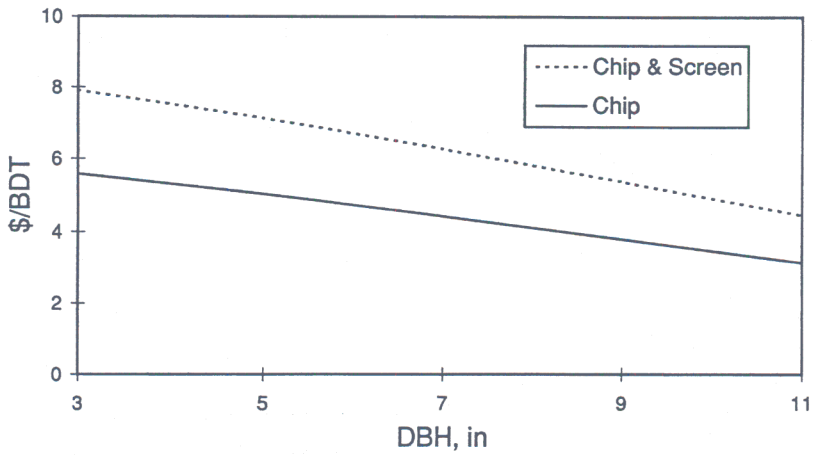

Figure 4. — Estimated chipping or chipping/screening costs.

(43,560 ft.^{2}/ac. × trees/move)/
(trees/ac. × row spacing × rows/strip)

In the test stand, travel was not always straight or one way because of the leaning and down trees. The harvester also moved very frequently because of the stand conditions. For estimating production in future stands, we assumed that improved tree form would allow four rows to be cut on each strip. We also assumed that the harvester would move one tree spacing distance on each move and then cut a tree in each row before moving again.

Harvester cycle time relationships are shown in **Table 2.** All are highly significant (at the 1% level). Processing time increased with the specified level of debarking, and this is quantified in the regression relationship with the coefficients of the dummy variables: Partial and Full. Partial = 1 for partial debarking, = 0 otherwise. Full = 1 for full bark removal, = 0 otherwise. For Standard processing, both dummy variables are set to zero.

We were able to clearly identify some of the additional time spent dealing with forks and crooks, but these averaged only a few centiminutes per tree, as indicated in **Table 1.** There was considerable other time that could not be clearly separated; the forks and crooks reduced the feed rate through the head, and decreased the length of stem that could be processed before a reversal or bucking cut had to be made. In stands without heavy leaners and down trees, logs can be piled on both sides of the harvester. This speeds processing because trees do not have to be rotated or moved as far. The trees that were leaning or down also increased felling times by restricting the directions from which the trees could be cut, and by requiring the operator to be more cautious to avoid hitting the ground with the chainsaw. In addition, brushing would almost be eliminated in higher quality stands of more uniform trees. Considering all of these factors, we estimated that harvester productivity would be increased by 30 percent or so in future stands of good quality compared to the one observed, for any given average tree size. Assuming 80 percent utilization, the productivity reported by Howe (10) is similar to our adjusted rate for complete debarking of trees of comparable size (just under a productive minute per tree

for 9 inch trees) so the adjustment seems reasonable.

The observed forwarder load size was only about 3 BDT or 6 green tons, about half the nominal capacity of the forwarder. This was due to poor packing of the relatively crooked logs, and due to the short lengths of many of the logs. With better trees, a higher percentage of the logs could be cut to maximum lengths, packing should be improved, and higher stakes could be used if needed. To estimate productivity in future stands of good quality, we assumed a forwarder load size of 12 green tons.

As noted earlier, a front-end loader was used to feed the Morbark 20 chipper during the trial. A separate loader or skidder is commonly used to break down decks of whole trees, and in some cases with cut-to-length logs. Using a chipper with an infeed deck, however, it is possible to chip at high rates directly from cold decks of CTL logs, thereby eliminating the cost of the loader or skidder. We therefore used results from a CTL study where a Morbark 27 fed itself from cold decks (2):

Total productive time per load,
cmin = (1103. + 145.06 ×
VanWeight – 9.99 × LogWeight) ×
(1 + ChipProductiveDe-lays)

ChipProductiveDelays,
fraction of cycle time = 0.11

where:

VanWeight = net chip van weight in green tons
LogWeight = average weight per log in green pounds

Costs were estimated at about $95 per productive hour (PH) for the harvester, $78/PH for the forwarder, $95/PH for a Morbark 27 chipper, and an additional $40/PH if the screen is included in the system. These were calculated with the machine cost approach (1,12), assuming 80 percent utilization for all equipment, 5-year lives for the harvester and forwarder, and 7-year lives for the chipper and screen. We assumed purchase prices of $250,000, $200,000, $260,000 and $180,000 for the harvester, forwarder, chipper, and screen, respectively. A spreadsheet was developed to calculate cycle times, productivities, and costs per BDT of clean chips. Estimated harvesting, forwarding, and chipping/screening costs per BDT over ranges of tree size and operating conditions are displayed in **Figures 2, 3, and 4**, respectively.

Production rates for a single harvester, forwarder, and chipper are shown in **Figure 5**. For trees in the 5- to 11-inch DBH range, a reasonably balanced system would include three harvesters, two forwarders, and one chipper.

STUMP HEIGHTS

Initially, the harvester operator tried to cut fairly low stumps, but he was dulling the chainsaw frequently because of the gravelly soil and lack of duff and litter. He then cut higher stumps, which solved the dulling problem. Stumps, however, averaged 10.3 inches tall. This compared with an average of 4.8 inches for stumps left by a shear-equipped feller/buncher in an adjacent stand on similar terrain (**Fig. 6**).

The average difference in height, 5.5 inches, was somewhat more than the difference of 3 inches observed in a sawhead versus shear comparison conducted in Virginia (13). Sawn stump heights could be lowered with additional experience, and possibly by adding a spacer on the bottom of the harvester head to provide a gap between the saw and the ground. The leaning trees increased the stump heights because the head had to be raised to avoid contacting the ground with the saw chain. There also should be fewer problems with dulling the chain in soils with less rock. However, the duff and litter layer in short-

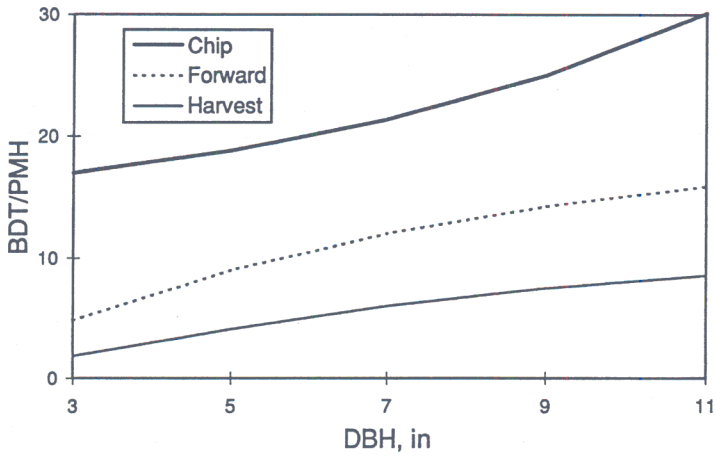

Figure 5. — Production rates per productive machine hour for a harvester (full debarking), a forwarder (500 ft. average distance), and a chipper.

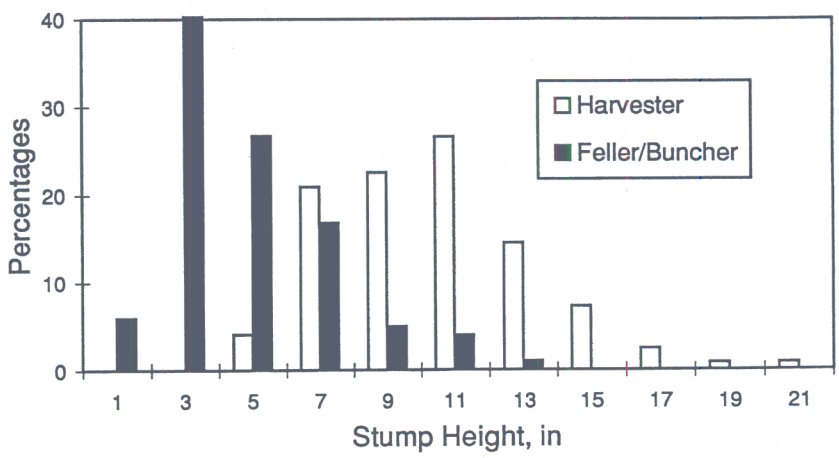

Figure 6. — Distribution of stump heights, for trees cut by a shear-equipped feller buncher and by the chainsaw-equipped harvester.

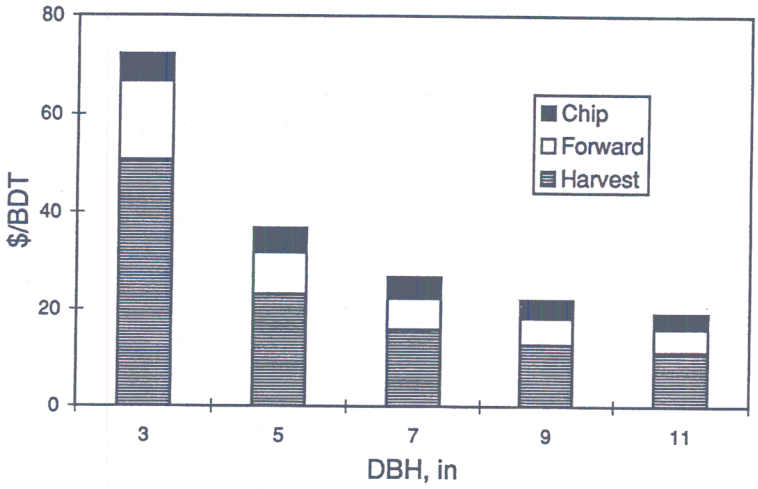

Figure 7. — Stump-to-truck costs for harvesting (full debarking), forwarding (500 ft. average distance), and chipping.

TABLE 3. — Overs, fines, and bark contents and numbers of observations for the tested screening and debarking treatments.

	Screened (*n*)	Unscreened (*n*)
	(%)	
Overs	4.3 (7)	6.1 (3)
Fines	0.3 (7)	0.9 (3)
Bark		
Full	1.6 (4)	1.5 (2)
Partial	5.7 (1)	3.7 (1)
Standard	3.4 (2)	no data

rotation plantations will probably remain rather thin so it is likely that shear heads will always be able to cut lower stumps than chainsaw heads.

BARK, OVERS, AND FINES CONTENTS

Unfortunately, we had only a few chip samples for each combination of treatments, so the results are rather fuzzy. Full debarking effort by the harvester reduced the bark content significantly (at the 5% level) in comparison to partial/standard debarking (**Table 3**). There was no significant difference between the screened and unscreened bark contents. In fact, the average was higher for the screened samples. This reflects random variability rather than an "addition" of bark in the screening process. Although it was assumed that a higher fraction of the bark than the wood would be in the reject size categories, this was apparently not the case. As expected, screening did significantly reduce (at the 5% level) overs and fines percentages.

For full debarking with or without screening, the observed average bark content of about 1.5 percent still exceeded the desired threshold of 1 percent. On trees of better form, bark content should be less. It was difficult or impossible to remove much of the bark near crooks or forks because the harvester knives and rollers could not contact the boles. Also, the trees in the test stand had not been irrigated during part of the growing season just before harvest. Continuing to irrigate until shortly before harvest might lower wood-bark adhesion and improve debarking results. Bark-wood bond strength varies with season, although there may be less variation for eucalypts that grow all year than for deciduous hardwoods. Studies in natural stands in Australia found less than a two-to-one variation in bond strength between winter and summer, and that sapwood MC was an excellent predictor of bond strength (14).

Bell representatives indicated that debarking might improve as the feed rollers were partially worn down, because bark might not clog the gaps between the cutting edges on the rollers. They also expected the use of the more aggressive, single-bevel delimbing knives to improve bark removal. They reported good results with these knives in South Africa. Other modifications that might help:

- a third feed roller, or hourglass-shaped rollers, to increase contact with the bark;
- slightly angled roller shaft axes to impart a slicing action between the roller cutting edges and the tree, and to produce a spiral motion of the stem through the head.

If bark content is still too high, it would be possible to process the logs through a flail/chipper rather than a stand-alone chipper. The disadvantage, of course, is the higher hourly cost of the flail/chipper, roughly half again as much as a chipper of equal productivity.

SITE PREPARATION AND OTHER EFFECTS

After harvesting, the test stand was allowed to coppice regenerate, so there was no difference in site preparation or regeneration costs on this versus a coppiced whole-tree site. Simpson replants the majority of its stands. If the stand had been planted, it was estimated that site preparation costs would have been increased by about 40 percent due to the higher stumps and residues. Increased fire danger is another possible negative. Expected benefits of the residues would include additional nutrients and higher soil MC during late spring due to the mulching effect.

DISCUSSION AND CONCLUSIONS

In clonal stands of trees with better form, and with minor changes to the harvester to improve debarking, the harvester- forwarder-chipper system may be able to produce chips with bark contents of less than 1 percent. Then the question comes down to harvesting economics and secondary effects. Stump-to-truck harvesting costs for the system with full debarking effort and 80 percent utilization for all equipment are displayed in **Figure 7**. Since the three activities (harvesting, forwarding and chipping) can work independently with buffers between them, we assumed that the system could be roughly balanced by choosing the optimal mix of equipment, and that the balance could be fine-tuned by adjusting the number of scheduled hours.

The costs for the CTL system are similar to those reported for whole-tree systems. For example, stump-to-truck costs of $33/BDT (1991 dollars) were reported for a whole-tree feller/buncher-skidder-chain flail delimber/debarker system (8). The whole-tree system was operating in short-rotation poplar that averaged about 6 inches DBH. An estimate of $35/BDT (presumably 1995 dollars) was presented for a similar system, in poplar stands that were 7 to 8 years old (15). The results of this study indicate that the CTL system

might be cost competitive with a whole-tree system.

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