DELIMBING HYBRID POPLAR PRIOR TO PROCESSING WITH A FLAIL/CHIPPER

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ABSTRACT

Processing whole trees into pulp chips with chain flail delimber/debarker/chippers (DDCs) is costly. Production rates of DDCs are limited by the residence time required to remove limbs and bark. Using a pull-through delimber, we delimbed trees prior to flailing and chipping, with the objective of speeding up the latter processes. Pre-delimbing increased the productivity of the DDC by about 10 percent. The reduced cost of flail/chipping did not cover the additional cost of delimbing with the machine mix tested, but changes to equipment and operating conditions might improve the situation. In the test configuration, the delimber processed 175 trees per productive hour, about half as many as the DDC. Delimbing separated about 35 dry pounds of limbs per tree, which may have higher value than the mixture of limb and bark residues produced by the DDC from whole trees.

Several paper companies in the Pacific Northwest are growing hybrid poplar in plantations on short rotations (less than 10 yrs) to supply some of their fiber needs. In the normal harvest sequence, these trees are mechanically felled and bunched, then forwarded to a landing with either a large front-end log loader or a grapple skidder. At the landing, the trees are delimbed and debarked with a chain flail processor, then chipped with a disc chipper (7,15). In most cases, the flail and chipper are combined into a single delimber/debarker/chipper (DDC).

Numerous studies have investigated the production rates of flails and/or the quality of the chips produced, including bark content (1,4,6,14). One of the limitations to a chain flail's productivity is the volume of residues (limbs, leaves, and bark) that must be separated from the bole wood and handled, especially during the summer months when fresh foliage is present. The residue takes up space in the flail's infeed and thus reduces capacity. In DDCs, the residue frequently bridges over the waste discharge chute, slowing production, reducing chip quality, and occasionally requiring that the machine be shut down and cleaned out. The large volumes of waste may also add to the following costs of operating the DDC: fuel, maintenance, and chain wear. Chain costs constitute a major part of total delimbing and debarking cost (13). Chains have been found to last as little as 12 or fewer loads, or in some cases up to 70 loads of chips (3).

The waste stream from the flail is of low value; it may be utilized for fuel or compost, or if the value is too low it is piled and burned on site. If limbs can be separated from the bark portion of the residues, they may be suitable for a higher value use such as feedstock for the neutral sulfite semi-chemical (NSSC) pulping process that furnishes pulp for corrugated cardboard.

Given the possible increase in value if the limbs can be separated, and the potential to increase flail/chipper productivity if the trees are delimbed prior to flailing, we decided to investigate alternatives to separate the activities. The possibilities included single-grip processors, irongate delimbers, and pull-through delimbers, among others. A pull-through delimber was selected for this study because it was inexpensive and an excavator was available to feed it. Irongates are also inexpensive, but must be fed by skidders, rather than by the front-end loaders that have been

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Figure 1. — Volvo front-end loader transporting whole trees.

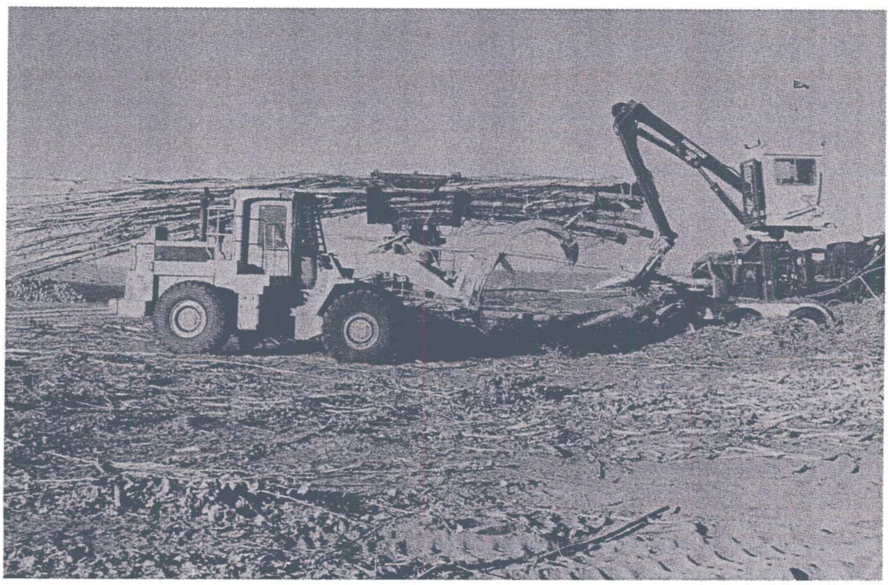

Figure 2. — Delimbed trees being delivered to the DDC. The loader in the foreground handles the residues produced by the DDC.

found to be effective for forwarding short-rotation trees (12).

The objectives of this study were to:

1. Determine the productivity of a pull-through delimber when processing 6-year-old hybrid cottonwood trees;

2. Determine the effects of delimbing prior to flail debarking on:

a) DDC productivity;

b) Costs of delimbing, debarking and chipping;

c) Chip quality;

d) DDC fuel usage;

e) Flail chain wear;

f) Recovery of clean chips, limb material, and other residues.

Approach

Operation studied

The study was conducted at Boise Cascade Corporation's Sand Lake Fiber Farm near Boardman, Oregon, during September 13-17, 1999. Trees were felled 7 to 9 days before they were processed, to promote partial drying and dropping of the foliage. On September 13 and 16, a Peterson Pacific DDC 5000 flail/chipper processed whole trees. On the 15th and 17th, it processed delimbed trees.

A Danzco PT20H pull-through delimber was placed in the precut unit, a few hundred feet from the road. A Volvo BM L150C front-end loader delivered bunches of whole trees to the delimber (**Fig. 1**), moved delimbed trees to the DDC (**Fig. 2**) or to a storage deck, and cleared limbs from in front of the delimber (**Fig. 3**). A Link Belt 2700 excavator with log grapple picked up the whole trees and pulled them through the delimber (**Fig. 4**). Delimbing productivity was only about half that of the DDC, so the excavator and delimber ran the whole week to prepare enough trees for the 2 days of DDC processing tests.

The Volvo loader was capable of keeping both the DDC and the delimber supplied with trees. A Cat 966D front-end loader equipped with a Shamrock slash grapple moved residues from the DDC's bark discharge, chipper reject, and infeed areas, and piled them for processing or burning at a later date.

An experienced and capable operator ran the DDC with similar control settings on all days (with one exception, noted later). Only two of three flails were run: the bottom drum and the front top drum. Both were set at the minimum speeds (approximately 80% of maximum speed). The operator used the same speed on the delimber feed roller and the chipper feed roller throughout the test. He changed chipper knives at the end of each day (or earlier if they became dull), and honed them halfway through the shift. Every day, all chains on the upper drum and half of those on the lower drum were changed.

Data collection

Delimbing productivity and quality. We used time-motion study to evaluate delimbing productivity and quality. We divided the delimbing cycle per grapple load of trees into the following elements:

Pick up trees and place them in the delimber;

Limb (pulling through the delimber);

Deck stems after they have cleared the delimber;

Move the loader when it is not carrying stems;

Other productive time including piling residues.

We recorded delays separately by type. We counted trees per cycle and made occular estimates of tree diameter at breast height (DBH) and the percentage of limbs removed. For the latter, we used classes of removal: 1 = 0 to 20 percent removal; 2 = 21 to 40 percent; 3 = 41 to 60 percent; 4 = 61 to 80 percent; 5 = 81 to 100 percent. All the information was recorded on a Husky Hunter computer equipped with SIWORK3 time study software (8).

DDC productivity and chip quality. — We recorded chipping and other productive times per van, delay times by type, number of stems per van, and number of DDC grapple loads per van. Net green weight per load was taken from load tickets. A chip sampling tube was fabricated out of PVC pipe and elbows. Samples were collected from each van load by placing the tube under the chipper's discharge spout for a fraction of a second at four or five times throughout the chipping of the load. All the sample chips (about 5 kg) from a load were placed in a bucket, which was topped and then rolled to mix the chips. Two subsamples of approximately 800 g each were taken from the bucket and analyzed for moisture content, bark content, and size distribution.

DDC fuel usage. — A totalizing fuel flow meter was installed on the DDC. A reading was taken at the beginning and end of the chipping of each load, and at the beginning and end of any major delays within a load so that fuel used during the actual chipping of each load could be calculated.

Flail chain wear. — A new set of seven chains (eight links per chain, 5/8 in. nominal diameter) was installed on one row of the lower flail drum at the beginning of the first day of chipping whole trees. These chains were removed at the end of the day and reinstalled for the second whole-tree day, in the same order on the drum and with the same ends of the chains attached to the drum. The set of chains was weighed when new and at the end of each of the 2 days of chipping. At these same times, we used a caliper to measure the smallest thickness on the third link (with the outermost original link designated as the first) on each of the seven chains. Previous studies have indicated that the second or third link experiences the most wear (2,11). A different set of chains was installed for the 2 days when delimbed stems were chipped, and we recorded the same data as for the whole tree set.

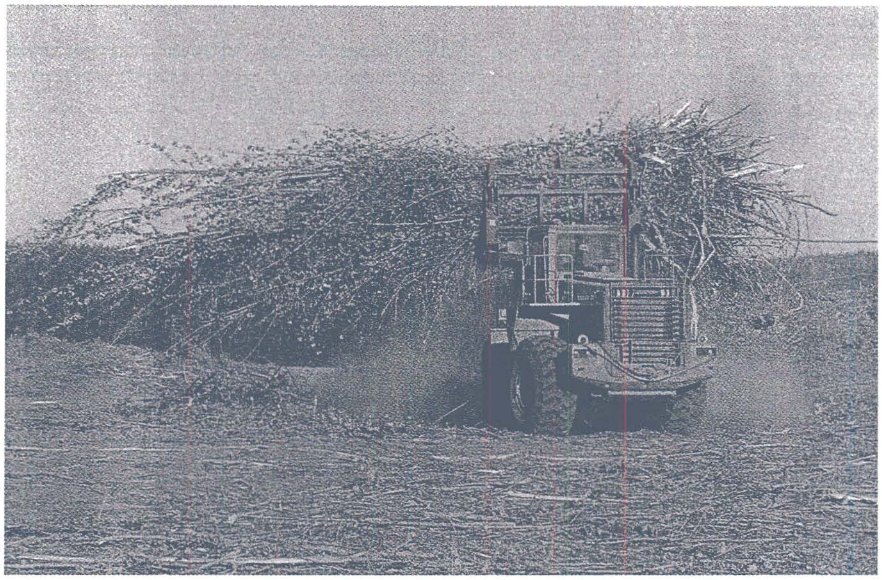

Figure 3. — Volvo front-end loader moving limbs from the delimber.

Figure 4. — Link Belt excavator with grapple, pulling trees through the Danzco delimber.

Recovery of clean chips, limbs, and other residues. — We collected material removed by the delimber by having the Volvo operator set aside most of the residues from eight batches of counted stems. The numbers of stems per batch ranged from 76 to 166. (A small fraction of the residue - probably about a tenth of the total - fell between the delimber and excavator and could not be collected by the front-end loader.) The residues from each batch were loaded into a skidder-towed trailer or a dump truck, and weighed on a truck scale. For each batch, we then calculated the delimber residue weight (green) per tree.

For three van loads of whole trees and four loads of delimbed trees, the bark discharge material and (separately) the chipper rejects were set aside. These were hauled by dump truck to the scale

TABLE 1. — Summary of study time and production.[a]

	Delimbing	Debarking/chipping of delimbed trees	Delimbing/debarking/ chipping of whole trees
Total study time (hr.)	19.90	17.98	19.78
Productive time (hr.)	16.55	14.66	15.97
Trees processed	2891	5303	5073
Trees/PMH	175	382	318
Van loads produced		28	28
Chips produced (ODT)		420.3	417.9
ODT/PMH		28.7	26.1

[a] PMH = productive machine hour; ODT = ovendry tons.

TABLE 2. — Danzco delimber productivity statistics.

Variable	Mean	SD[a]	Range	*n*
Trees	3.50	0.84	1 to 5	826
DBH (in.)	6.50	0.85	4.3 to 11.0	826
Basal area (in.^{2})	115	26	28 to 205	826
Removal class	3.54	0.81	1 to 5	821
Cycle elements (cmin/grapple load)				
Pick	38.5	17.4	0 to 141	826
Limb	37.3	17.6	12 to 171	826
Deck	22.5	8.0	0 to 57	826
Move	17.9	5.7	0 to 46	826
Other	2.0	17.3	0 to 802	826

[a] SD = standard deviation.

TABLE 3. — Regression relationships for pull-through delimbing.[a]

Variable	Relationship	r^2	*n*
Trees per cycle	7.2 – 0.57 × DBH	0.33	826
Removal class	3.91 – 0.0055 × Basal area	0.03	821
Cycle elements (cmin/grapple load)			
Pick	32.3 + 1.76 × Trees per cycle	0.01	826
Limb	28.8 + 0.023 × Removal class × Basal area	0.02	821
Deck	16.7 + 1.66 × Trees per cycle	0.03	826
Move	17.9	(s = 5.7)	826
Other	2.0	(s = 17.3)	826

[a] where trees per cycle = trees per grapple load; removal class = delimbing removal class (1 to 5); basal area = total basal area of the trees in the grapple load (in.^{2}); DBH = mean diameter at breast height of the trees in the grapple load (in.)

and weighed. From the tree counts for each van load, we then calculated the following weights per tree: chips into the van, bark discharge material, and chipper rejects.

Results and Discussion

The study observations are summarized in **Table 1**.

Delimbing Production Rate

The Link Belt operator spent two-thirds of the total productive time in two activities: picking trees out of the pile of whole trees, and pulling them through the delimber arms (**Table 2**). The operator delimbed between one and six trees per cycle (**Fig. 5**), averaging 3.5. (When trees are being processed for sawlogs, they are usually processed one at a time.)

On average, the Link Belt/Danzco combination delimbed 175 trees per productive hour. The regression relationships developed from the data are displayed in **Table 3**. With the exception of *Pick* (p = 0.02), all the relationships were highly significant ($p < 0.01$), but they only explained small fractions of the variation in the data. On average, fewer trees were delimbed with each pull if the trees were larger in diameter. The time to pick up stems increased with the number of trees grappled, as did the time to deck delimbed stems. Most of the decking time involved moving the tops of the trees laterally, away from the line of the delimber. It appeared to be a motion that could be avoided by clearing the delimbed stems more frequently or by adding an angled ramp that would cause the tops to slide laterally. Delimbing took longer if more basal area was processed at the same time, and if the removal quality was higher.

Combining all the relationships allows one to estimate delimbing productivity for various conditions; **Figure 6** shows how productivity was on average affected by tree diameter.

Because the excavator's reach was limited, it had to travel about 40 feet each way on each delimbing cycle to index the butts of the trees to a common point, determined by the length of the tallest trees. Travel by a crawler undercarriage is considerably slower than swinging, so a longer boom would be preferable.

We observed one repositioning of the delimber by the Link Belt excavator from one landing to the next; this took 8 minutes.

Delimbing Quality

On average, delimbing removed approximately 60 to 70 percent of the limbs, based on our visual estimates. Removal percentage was highly variable and decreased slightly as total basal area per grapple load increased.

Several factors limited the delimbing quality. Obviously, handling multiple stems simultaneously prevented the delimbing knives from fully removing branches between the stems, but three other aspects also contributed to the problem. The loader grappled stems 2 to 4 feet above the butts to prevent them from slipping out of the grapple. The delimber knives were another 4 feet or so beyond where the grapple could place the trees in the delimber. As a result the delimber could not remove the limbs on the lowest 6 to 8 feet of each stem. The trees from the edge of the plantation, especially, had many low branches. Many of these limbs were dead and brittle, however, so they probably contributed little to the flail's burden.

Single tops of many trees were too light to hold the delimber's activating treadle down, so the knives opened prematurely, resulting in poor delimbing of these tops. Tree malformations (crooks, forks, and the occasional heavy limb) could not be pulled through the knives. The Link Belt operator had to lift the stems off the treadle to open the knives, pull the bad portion through, set the stems down again, and continue pulling. But there was a delay between setting the stems down and full closure of the knives, so the sections just beyond the crook or fork were not delimbed either.

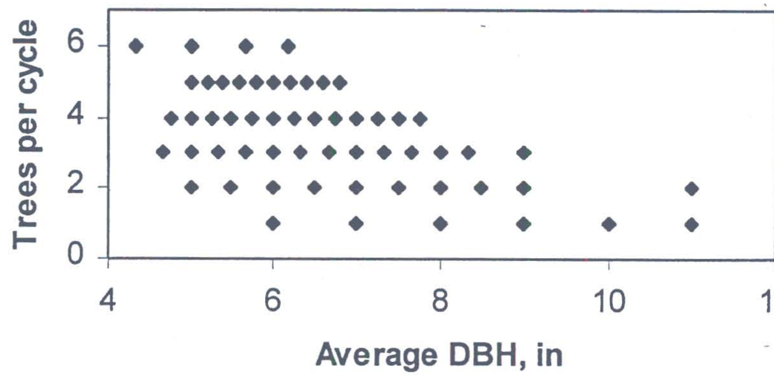

Figure 5. — Trees per grapple load for delimbing versus average DBH per grapple load.

DDC PRODUCTION RATE

Statistics for the DDC are shown in **Table 4**. The independent variables for the whole tree and delimbed cases were very close on average; bone dry content averaged 54.1 percent for both, and chip weight per tree averaged 165 and 159 dry pounds for whole and delimbed trees, respectively, giving a fair comparison of chipping rates.

On a per-load basis, chipping rate averaged 29 ovendry tons (ODT) per chipping hour and ranged from 21 to 37 ODT/hr. The production rate for delimbed stems was 8 percent higher than that for whole trees, and the difference was significant ($p = 0.02$). Eight of the 10 most productive loads were of delimbed trees, and 8 of the 10 least productive were of whole trees.

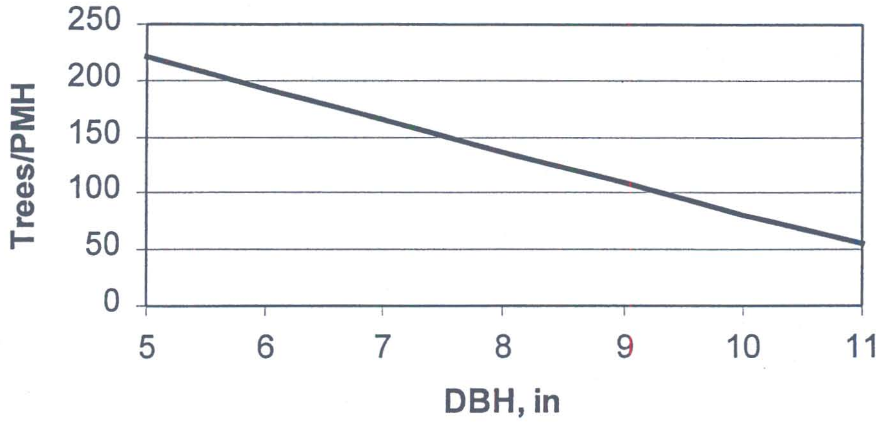

Figure 6. — Delimbing productivity versus average DBH.

The DDC operator fed 13 percent more delimbed trees than whole trees with each grapple load, and this difference was also significant ($p = 0.02$). It appeared, however, that feeding of the delimbed stems was less uniform than for whole trees. This was caused by 1) the difficulties with handling stems that were broken during delimbing and subsequent decking; and 2) extra handling to pull in stems whose butts were not indexed with the others. We noticed both of these problems on the first day of chipping the delimbed stems, but they diminished on the second day. It appeared that the Link Belt operator did a better job of indexing the stems as the trial progressed, and that the Volvo operator stacked the delimbed trees in decks of less height, which seemed to reduce breakage.

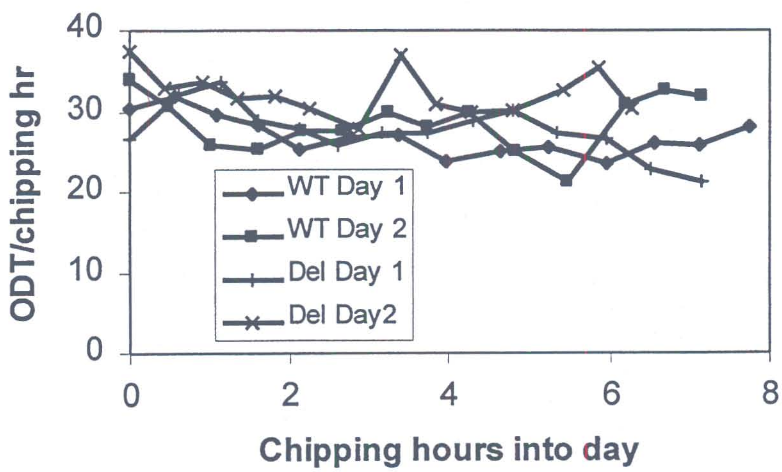

Figure 7. — Chipping productivity for each load versus chipping hours completed before beginning the load.

DDC production rate decreased over the course of each day, for both delimbed and whole trees (**Fig. 7**). The rate dropped by about half an ODT per hour, for each productive hour into the day. We'd guess that the decrease was caused mostly by operator fatigue, although dulling of chipper knives also played a role.

Chipping rate increased with average tree size, calculated from the load weight and tree count for each load. We developed a regression relationship that re-

TABLE 4. — *Peterson-Pacific DDC 5000 productivity statistics.*[a]

Variable	Mean	SD	Range	*n*
Chip (cmin/load)				
Whole tree	3251	340	2674 to 4123	28
Delimbed	3047	428	2378 to 4082	28
Switch vans (cmin/load)	99	63	0 to 267	56
Other productive delays (cmin/load)	34	102	0 to 662	56
Move between landings (min/move)	45	- -	- -	1
Trees per load				
Whole tree	181	22	134 to 226	27
Delimbed	189	18	161 to 235	28
Load weight (green tons)				
Whole tree	27.6	1.8	25.6 to 31.9	28
Delimbed	27.7	2.0	26.0 to 33.0	28
Load weight (ODT)				
Whole tree	14.9	1.1	13.2 to 17.0	28
Delimbed	15.0	1.3	13.4 to 18.4	28
Chip weight per tree (OD lb.)				
Whole tree	165	16.0	140 to 201	27
Delimbed	159	14.4	140 to 208	28
Grapples per load				
Whole tree	65.4	6.8	53 to 78	14
Delimbed	62.9	9.7	47 to 80	17
Trees per grapple				
Whole tree	2.66	0.39	1.97 to 3.23	14
Delimbed	3.10	0.44	2.27 to 3.87	17
Production (ODT/chipping hr.)				
Whole tree	27.8	3.0	21.1 to 33.8	28
Delimbed	30.0	3.8	21.3 to 37.4	28

[a] SD = standard deviation; OD = ovendry; ODT = ovendry tons.

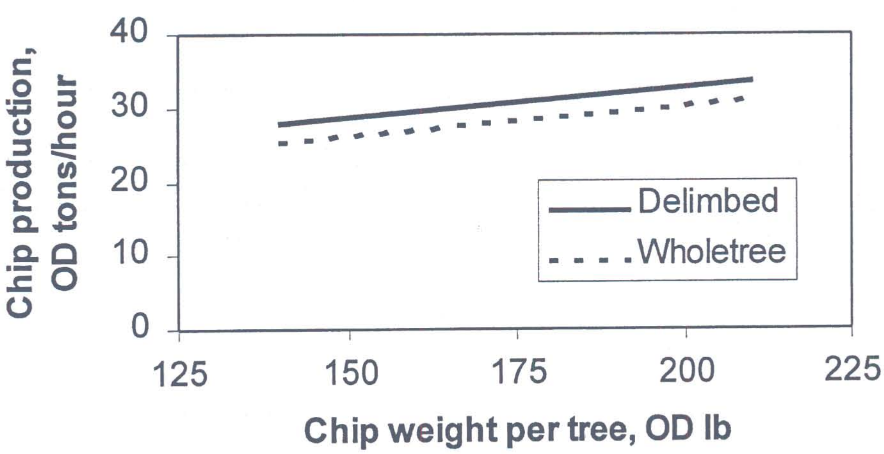

Figure 8. — DDC production rate versus tree size and type of tree, after 4 hours of chipping.

flected the effects of time of day, type of tree, and tree size:

$$\text{Chipping rate} = 16.6 - 0.63 \times \text{Hours} + 2.5 \times \text{Delimb} + 0.081 \times \text{Chip weight per tree}$$

$$r^2 = 0.31 \qquad n = 55$$

where Chipping rate = ODT produced per chipping hour; Hours = chipping hours, at the start of the load, since the beginning of the shift; Delimb = a dummy variable with a value of 1 for delimbed trees, 0 for whole trees; Chip weight per tree = ovendry pounds of chips per tree.

All terms were highly significant ($p < 0.01$). The effects of tree size and delimbing status are shown in **Figure 8**.

It may have been possible to increase the production rate for delimbed trees by adjusting the chipper conditions. During the last two loads, the DDC operator raised the chipper infeed roller so it would not constrain the chipper. The next-to-last load was the third most productive of the trial, at 35.4 ODT/chipping hour. (The chipper knives became dull during the last load, reducing productivity to 30.3 ODT/chipping hr.) Raising the chipper infeed roller or increasing the speeds of the delimber infeed rollers would probably have increased chipping rate. As noted earlier, trees were cut a week or more before processing to allow the foliage to dry. If the trees were pre-delimbed, the drying period would not be necessary. Bark is considered easier to remove on fresh trees because the wood-bark bond is weaker (5,9), so fresh trees could probably be processed at a faster rate.

CHIP QUALITY

Significantly fewer of the chips from delimbed trees were classified as acceptable by size: on average, 56 percent for delimbed trees versus 59 percent for whole trees ($p < 0.01$, $n = 109$). The additional non-acceptable chips showed up as significantly more oversize, overthick, and overlength chips (**Fig. 9**). This might be due to the additional breakage of delimbed trees. There were no significant differences in pins, fines, or bark contents. The latter averaged 2.6 percent.

CHIP SAMPLE VARIABILITY

Samples constitute a minute fraction of a van load, so it is questionable whether a sample is representative of any single van. With our sampling method, the two 800-g subsamples per van were both taken from a total sample of no more than about 5000 g, so each represented roughly a 20 percent subsample. Even for these, the variability was rather high; the magnitude of the difference averaged 2.1 percent.

We sampled at several points for each van, while traditional mill samples come from a single point. We compared our sample results with the mill results on ovendry percentage for the six loads where we had both (**Fig. 10**). On average, the mill ovendry percent was 3.5 percent higher than ours, but in the extreme case the values were quite different: 60 percent for the mill sample versus 48 percent for our sample. This indicates a need to collect many (or larger) samples to obtain good estimates of mean values.

Fuel consumption

Chipping the delimbed trees consumed significantly less ($p = 0.01$) fuel per ODT than did chipping whole trees (**Table 5**). The difference of 8 percent was essentially equal to the difference in production rate between the two materials, as consumption per chipping hour was the same for both. (Fuel consumed by the chipper while switching trucks and during all other delays was equivalent to only 3% of that used while chipping.)

We did not record fuel consumption for the Link Belt excavator or Danzco delimber, but we estimate that this fuel slightly more than offset the reduction in fuel used for chipping (**Table 5**).

Chain wear

The tons of chips produced each day were almost identical, so chain wear per day (**Table 6**) can be compared directly. There was little weight loss (about 2 percent the first day and another 4 percent during the second day) and no significant differences between losses for the whole tree and delimbed cases.

Thicknesses of the third links diminished by an average of 27 percent during the first day, and an additional 12 percent (of original thickness) during day two. The chains used with the delimbed trees lost a percent more thickness, but the difference was not significant.

Delimber and DDC residues

The average weights per tree for three whole-tree loads and four delimbed loads are tabulated in **Table 7**. Delimber residues averaged 32 green pounds per tree. We adjusted this upwards by 10 percent (to 35 lb.) to account for the residues that could not be collected from the delimber.

Delimbing prior to flailing reduced bark discharge residues significantly ($p = 0.01$), by approximately half. Chipper rejects and total residues per tree were not significantly different, but the number of observations was small.

The pull-through delimber may remove some whitewood that the flail would not, lowering the recovery of high quality chips. Some wood was obviously broken off at the delimber, but the flail might also have removed much of this if the stems had not been delimbed. The Volvo operator noticed more break-

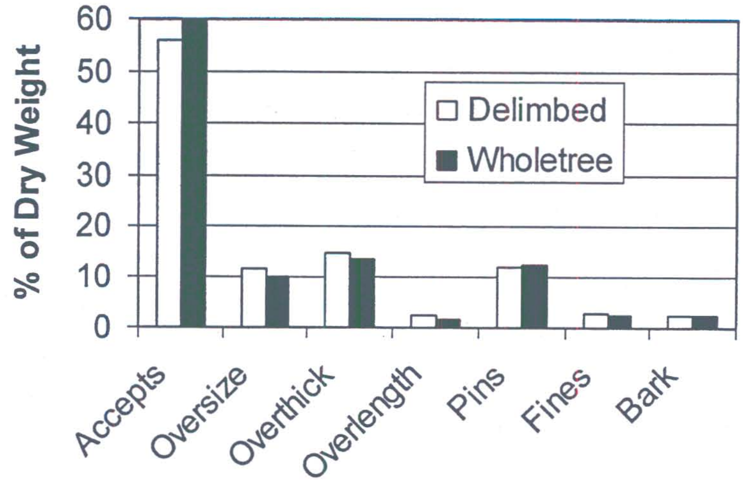

Figure 9. — Chip classification for delimbed versus whole trees.

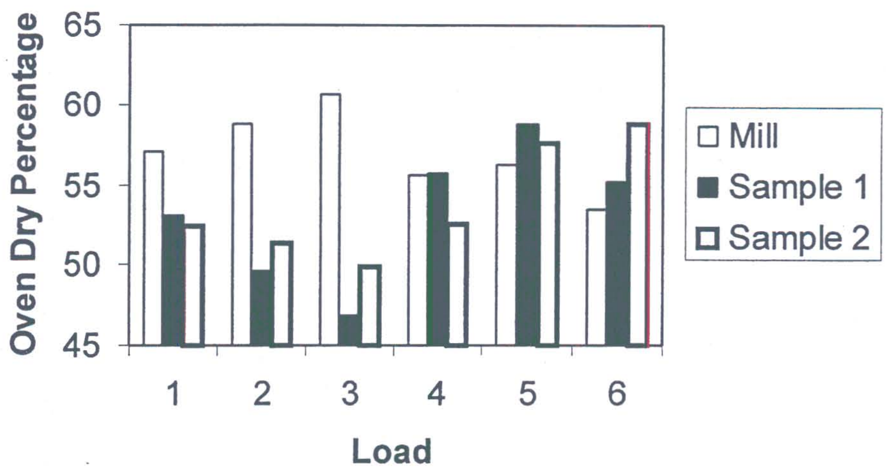

Figure 10. — Ovendry percentages for mill samples and our samples, for six loads

TABLE 5. — Fuel consumption statistics.[a]

	Mean	SD[a]	Range	Count
Fuel consumption(gal./ODT)				
Whole tree (DDC only)	1.33	0.14	1.11 to 1.68	26
Delimbed				
DDC	1.22	0.16	1.00 to 1.64	28
Link Belt + Danzco (est.)	0.18			
Fuel consumption (gal./PMH)				
Whole tree (DDC only)	36.2	2.7	32.4 to 43.7	26
Delimbed				
DDC	36.2	3.0	31.1 to 48.7	28
Link Belt (est.)	2.2			
Danzco (est.)	0.2			

[a] ODT = ovendry tons; DDC = delimber/debarker/chipper; PMH = productive machine hour.

TABLE 6. — Chain wear statistics.[a]

	New	WT, Day 1	Del, Day 1	WT, Day 2	Del, Day 2
Thickness of chain link #3 from outer end (in.) ($n = 7$ for all observations)					
Maximum	0.618	0.508	0.452	0.431	0.388
Minimum	0.591	0.421	0.431	0.342	0.338
Average	0.602	0.448	0.437	0.370	0.362
Percent of new	100	74.5	72.7	61.4	60.2
Chain weight (kg per chain) ($n = 7$ for all observations)					
Maximum				1.95	1.95
Minimum				1.87	1.70
Average	1.99	1.96	1.96	1.89	1.87
Percent of new	100	98.2	98.2	94.6	93.9

[a] WT = whole tree; Del = delimbed.

TABLE 7. — Weight per tree, based on one observation for each of the seven van loads for which residues were weighed.

Material	Whole trees	Delimbed trees
Chips (green lb./tree)	289	289
Residues (green lb./tree)		
Bark discharge	90	39
Chipper rejects	8	11
Delimber residues (adjusted)		35
Total residues	98	85
Total (green lb./tree)	387	373
No. of observations	3	4

TABLE 8. — Costs and productivity for processing whole trees versus delimbing prior to processing.[a]

	Whole tree	Delimbed - observed	Delimbed - w/large excavator
Purchase prices ($1,000)			
Danzco PTH		27	27
Link Belt 2700		160	
Link Belt 3400			220
Peterson Pacific DDC 5000	610	610	610
Volvo L150	270	270	270
Cat 966	240	240	240
$/PMH			
Delimb		79	95
Process with DDC	429	429	429
Productivity (ODT/PMH)			
Delimb		13.4	26.7
Process with DDC	25.9	28.3	28.3
Cost ($/ODT of chips)			
Delimb		5.9	3.6
Process with DDC	16.6	15.2	15.2
Total	16.6	21.1	18.8

[a] DDC = delimber/debarker/chipper; ODT = ovendry tons; PMH = productive machine hour.

age due to multiple handling of the delimbed stems, but he delivered all of the broken pieces to the flail.

Assuming the average tree size was the same for both operations, the difference in chip weight per tree would represent the delimbing losses. For all 56 observed loads, the chip weight per tree was 4 percent less for the delimbed trees (**Table 4**), but the difference was not significant.

Economics

A comparison of the delimbed and whole-tree cases was run for a typical tree size: 7 inches DBH, 162 ovendry pounds of chips, and 19 ovendry pounds of limbs recovered at the delimber. Two scenarios were included for the delimber: one with the observed excavator and production rate, and a second with a larger excavator and twice the observed production rate (**Table 8**). Hourly costs were calculated with the machine rate approach (10), based on year 2000 purchase prices for current equipment. The hourly costs of the Volvo and Cat loaders were included with those of the DDC, as the DDC limits the production rates. The calculated DDC production rates per chipping hour were reduced by the observed 5 percent productive delays, including changing vans. A balanced system with the small excavator would include two delimbers with one DDC, whereas only one delimber would be needed if using the larger excavator.

Pre-delimbing increases the productivity of the DDC and therefore reduces the DDC cost per ton. The cost of pre-delimbing, however, is more than the savings for the DDC. Revenues must be considered as well, since net profit equals revenues minus costs. There are two possible differences in revenues. The increased DDC productivity would result in more revenue if the payment per ton and productive hours per year were both fixed. For the large industrial producers in the Pacific Northwest, however, it is more likely that the trees to be harvested each year would be fixed, so there would be no difference in revenue for chips. But if the separated limbs are of higher value, more revenue will be produced. The break-even differential value for the limbs can be found from:

$$\text{Differential} = (\text{TCD} - \text{TCWT}) / (\text{Limb Weight/Chip Weight})$$

where Differential = break-even increase in value for limbs ($/ODT of limbs); TCD = total cost of delimbing and DDC processing ($/ODT of chips); TCWT = total cost of DDC processing of whole trees ($/ODT of chips); Limb Weight/Chip Weight = ratio of recoverable limb weight to chip weight.

For the observed loader and delimber, the break-even differential is about $40/ODT of limbs. For the larger loader and higher productivity, the break-even would only be about $20/ODT of limbs, which may be a realistic increase in value.

Recommendations

The Danzco delimber appeared to slab off portions of stems that were even mildly crooked, and broke some bigger tops if the grip was too tight and/or a big limb caused the delimber to rear up. After some initial tests, the operator reduced the pressure setting on the delimber's hydraulic accumulator in order to reduce breakage, but some still occurred. A more stable base on the Danzco - an extended leg on the outfeed end or a weight on the infeed end - would help prevent the rearing motion and breakage.

In addition or alternatively, a remote override control of the delimber knives would help prevent slabbing and breakage, allow delimbing of light tops and improve delimbing beyond a fork or large branch. A top impactor such as on the John Deere 743 harvester (produced in the late 1970s) could knock off tops at a preset diameter (e.g. 2 in.) further reducing the "waste" material in the bark discharge and shifting the tops to the recoverable limb category.

The Link Belt operator felt that a larger excavator (220-size versus 150-size) would probably double delimbing productivity because the longer reach would eliminate the crawler travel on each cycle, and the increased slewing torque would allow more trees to be processed with each swing. A telescopic extension might also help to rapidly index the butts of the delimbed trees.

The decking motion could be eliminated by: 1) using a ramp so the tops would slide laterally away from the delimber; or 2) removing the tops with an impactor on the delimber.

Single-grip processors are inherently faster than pull-through delimbers for single stems. A single-grip head is not likely to process as many stems at once as did the Danzco, but single-grips have been used for multiple-stem delimbing in Scandinavia.

It might be possible to place a pull-through delimber directly in front of the DDC and feed both with the DDC's loader. It seems most efficient to couple the two activities in some fashion to eliminate the multiple pieces of equipment and the extra handling. With this configuration, the limb residues could still be separated from the others.

The steady decline in productivity over time during a single day shows that it is important to study an operation for complete days to obtain unbiased production data.

Conclusions

A grapple-equipped excavator and pull-through delimber processed multiple stems simultaneously, averaging 3.5 stems per pull in the trial. The delimber removed about two-thirds of the limbs from the hybrid cottonwoods, and these limbs would be available for a higher-valued market such as low-grade pulp. Productivity of the delimber was about half of that of the DDC, but the observed excavator was too small for the task. A larger machine might bring productivity up to near that of the DDC.

The DDC processed the delimbed trees 8 percent faster than whole trees, and might be able to increase that rate if trees were processed fresh and/or if the feed speed was increased. The DDC's fuel usage per ton was reduced by the same percentage, but total fuel consumption for delimbing, debarking, and chipping probably increased slightly. No obvious differences in flail chain wear were evident.

There were no significant differences in the amount of clean chips recovered per tree, but the accepts fraction was lower for the delimbed trees. This might be related to breakage during delimbing and related handling.

The projected costs of delimbing more than offset the savings in DDC costs, even if the delimber's productivity was doubled by using a larger excavator with the delimber. The combination might be economical if: 1) the value differential for recovered limbs was high enough; and/or 2) the delimber could be integrated into the flail/chipper so that the separate feed loader could be eliminated.

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