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DELIMBING HYBRID POPLAR PRIOR TO PROCESSING WITH A FLAIL/CHIPPER

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Summary. We compared the performance of a flail/chipper for processing a) whole poplar trees and b) poplar trees that had been roughly delimbed with a pull-through delimber. Production rate was about 10% higher for the delimbed trees. The reduced cost of flail/chipping would not cover the additional cost of delimbing with the machine mix tested, but changes to equipment 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 per tree of limbs, which may have higher value than the mixture of limb and bark residues produced by the flail from whole trees.

Keywords: Short-rotation forestry, delimbing, debarking, chipping.

Background

Several paper companies in the Pacific Northwest are growing hybrid poplar on short rotations (less than 10 years) to supply some of their fiber needs. In the normal harvest sequence on Boise Cascade's Cottonwood Fiber Farm in eastern Oregon and Washington, trees are felled and bunched with a conventional shear mounted on an excavator carrier, then forwarded to a landing with either a large front-end log loader or a conventional skidder. At the landing, the trees are delimbed, debarked and chipped with a Peterson Pacific DDC 5000 chain flail processor.

One of the limitations to the DDC 5000's productivity is the volume of residues (limbs, leaves and bark) that is generated and needs to be handled, especially during the summer months. The residue takes up space in the DDC 5000's in-feed system and thus reduces capacity. It also 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 add to the following costs of operating the DDC 5000: fuel, maintenance and chain wear. Chain costs constitute a major part of total delimbing and debarking cost (Stokes and Watson 1989). Chains have been found to last as little as 12 or fewer loads, and in some cases up to 70 loads of chips (Carte et al 1991).

The waste stream from the DDC is of low value; it may be utilized for fuel, 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: feedstock for an 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, it seems beneficial to investigate alternatives to separate the activities. The possibilities include 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 found to be effective for forwarding short-rotation trees (Hartsough and Spinelli, submitted).

Objectives

The objectives of this study were to:

1) Determine the productivity of a pull-through delimber for removing limbs from six-year-old hybrid cottonwood trees.
2) Determine the effects of delimbing prior to flail debarking on:
    A) Flail delimber/debarker/chipper productivity.
    B) Costs of delimbing, debarking and chipping.
    C) Chip quality.
    D) Flail debarker/chipper fuel usage.
    E) Flail chain wear.
    F) Recovery of clean chips, limb material and other residues.

Operation Studied

The study was conducted at Boise Cascade Corporation's Sand Lake Fiber Farm near Boardman, Oregon, during 13-17 September 1999. Trees were felled seven to nine days before they were processed, to promote partial drying and dropping of the foliage. On 13 and 16 September, the DDC 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 (Figure 1), moved delimbed trees to the DDC (Figure 2) or to a storage deck, and cleared limbs from in front of the delimber (Figure 3). A Link Belt 2700 excavator with log grapple picked up the whole trees and pulled them through the delimber (Figure 4). The grapple rotator was not working, but this did not appear to cause many delays. Delimbing productivity was only about half of that of the DDC, so the excavator and delimber ran the whole week to prepare enough trees for the two days of DDC processing tests.

On the days when whole trees were chipped, the Volvo front-end loader also carried whole trees directly from the feller buncher piles to the DDC; the loader was capable of keeping both the DDC and the delimber supplied. When the DDC processed delimbed trees, approximately half the trees delivered to the DDC came directly from the delimber, and the other half from decks of previously delimbed stems.

The DDC chipped directly into top-loading vans, which were pulled forward 10 feet or so as each portion of the van was filled. In most cases, an empty truck arrived before the current van was filled, so the empty truck pulled into place as soon as the previous truck pulled out.

A Cat 966D front-end loader equipped with a Shamrock slash grapple moved residues from the DDC. Residues from the bark discharge, chipper reject, and infeed areas were piled for processing or burning at a later date.

An experienced and capable operator ran the DDC with similar 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 max 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 when needed if they became dull), and ground the knives with a hand-held pneumatic grinder and fixture approximately halfway through the day. Every day, all chains on the upper drum and half of those on the lower drum were changed.

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

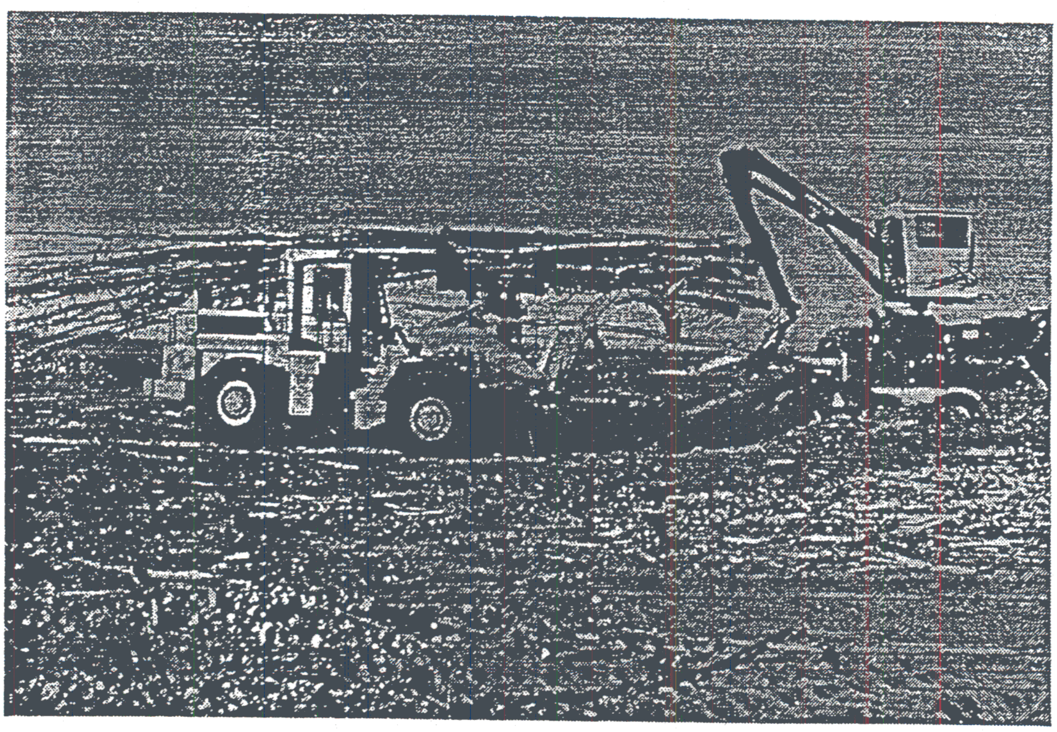

Figure 2. Delimbed trees being delivered to the DDC by the Volvo front-end loader. The Cat 966 front-end loader in the foreground handles the residues produced by the DDC.

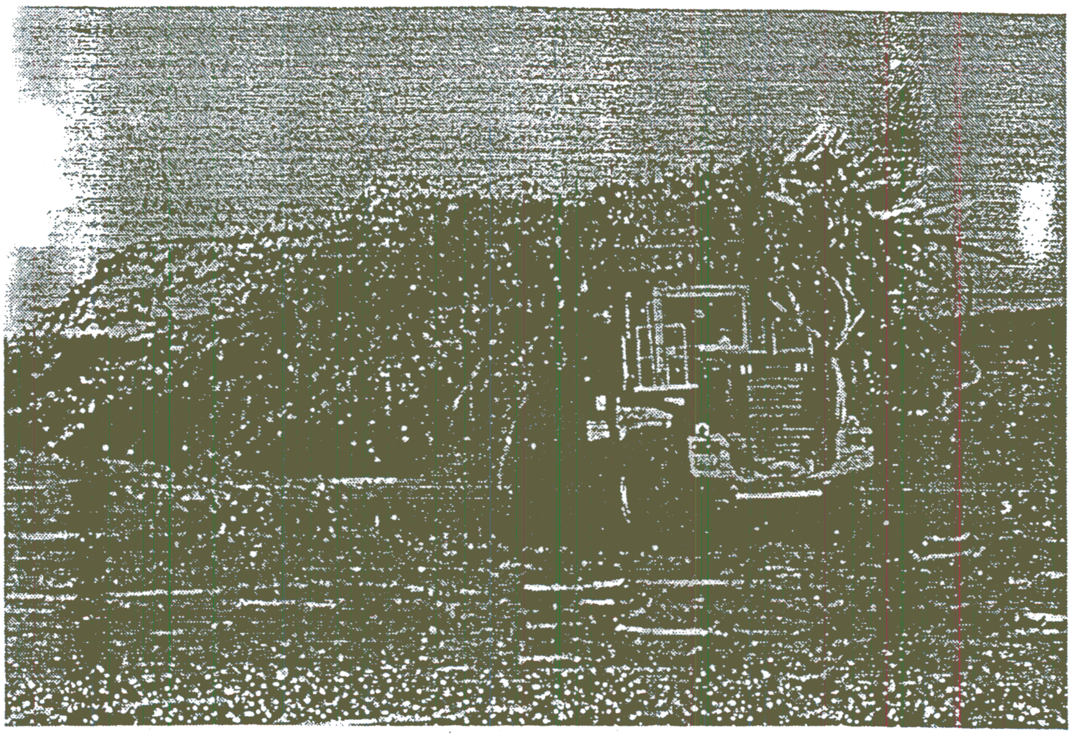

Figure 3. Volvo front-end loader moving limbs from the delimber.

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

Study Approach

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
- **pile** residue
- **other** productive time.

We also recorded delays by type, trees per cycle by DBH (eyeball estimates to the nearest inch), and eyeball estimates of the percentage of limbs removed. For the latter, we recorded classes of removal: 1 = 0-20% removal, 2 = 21-40%, 3 = 41-60% 4 = 61-80%, 5 = 81=100%. All the information was recorded on a Husky Hunter computer equipped with SIWORK3 timestudy software.

We did not record the time spent by the Volvo front-end loader to move stems to or from the delimber.

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 from a load were placed in a 5-gallon bucket. The bucket was topped, and then rolled to mix the chips. Two subsamples of approximately 800 g each were taken from the bucket, placed in ziploc bags and stored in ice chests. The samples were analyzed at the Boise Cascade lab for moisture content, bark content and size distribution.

DDC fuel usage. A totalizing fuel flow meter (resolution: 0.1 gallon) was installed on the DDC. The reading was recorded 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" 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 two 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 (Raymond and Franklin 1990, Carte et al 1990). A different set of chains was installed for the two days when delimbed stems were chipped, and we recorded the same data as for the whole tree set.

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. (The residues on the output side of the delimber were not collected. These probably represented about 10 percent of the total delimber residues.) 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 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/Discussion

The study observations are summarized in Table 1.

Table 1. Summary of study time and production.

	Delimbing	Debarking/Chipping of Delimbed Trees	Delimbing/Debarking /Chipping of Whole Trees
Total Study Time, hrs	19.90	8.99	9.89
Productive Time, hrs	16.55	7.33	7.99
Trees processed	2891	2652	2537
Trees/PMH	175	382	318
Van loads produced		14	14
Chips produced, ODT		210.1	208.9
ODT/PMH		28.7	26.1

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 (Figure 5). The operator delimbed between one and six trees per cycle, averaging 3.5 (Figure 6). This contrasts with the case where trees are being processed for sawlogs, where generally only one tree is processed at a time. A complete table of delimbing production statistics is included in the appendix.

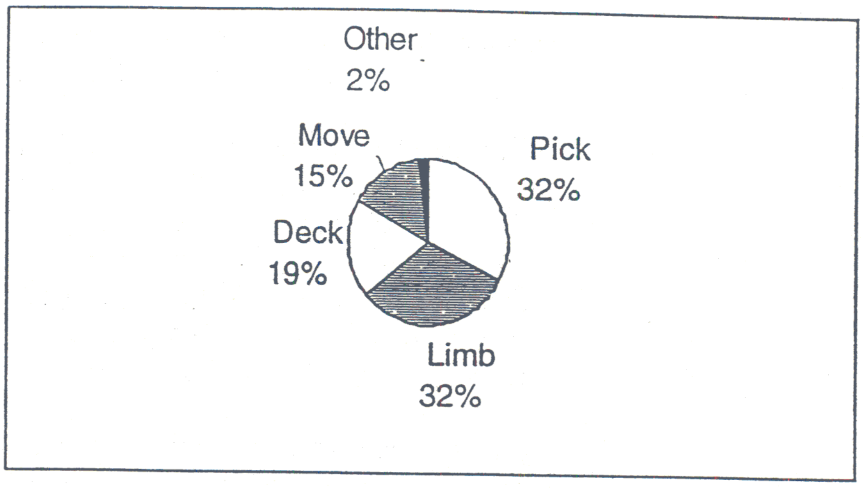

Figure 5. Delimbing cycle elements as percentages of total cycle time.

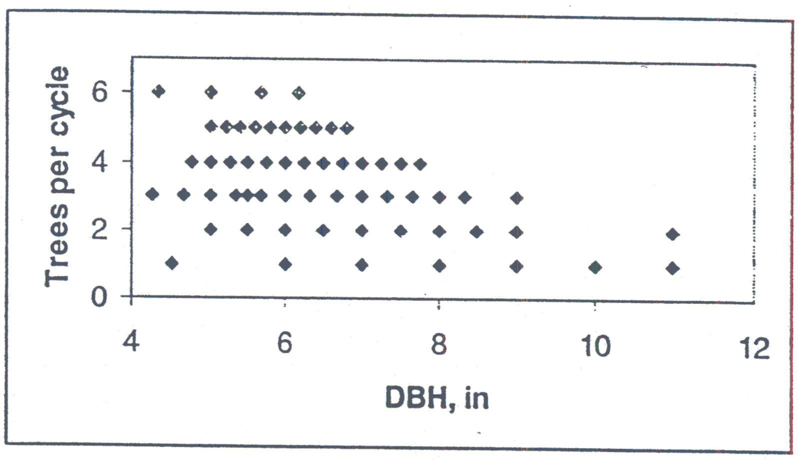

Figure 6. Trees per grapple load for Link Belt/Danzco delimbing.

On average, the Link Belt/Danzco combination delimbed 175 trees per productive hour. The regression relationships developed from the data are displayed in Table 2.

Table 2. Regression relationships for pull-through delimbing.

Variable	Relationship	R^2	n
Trees per cycle	7.0 – 0.54 * DBH	0.30	826
Removal class	3.91 – 0.0055 * Basal area	0.03	821
Cycle elements, cmin/grapple load			
Pick	32.3 + 1.76 * Trees	0.01	826
Limb	28.8 + 0.023 * Removal class * Basal area	0.02	821
Deck	16.7 + 1.66 * Trees	0.03	826
Move	17.9	(s = 5.7)	826
Other	2.0	(s = 17.3)	826

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

With the exception of pick ($p = 0.015$), 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. As might be expected, 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. The latter was probably an inverse cause-effect, i.e. more limbs were removed when the operator took more care and time while delimbing.

Combining all the relationships allows one to estimate delimbing productivity for various conditions. Based on the relationships, Figure 7 shows how productivity was on average affected by tree diameter.

Because the loader'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. Crawler travel is considerably slower than swinging, so a loader with longer reach 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.

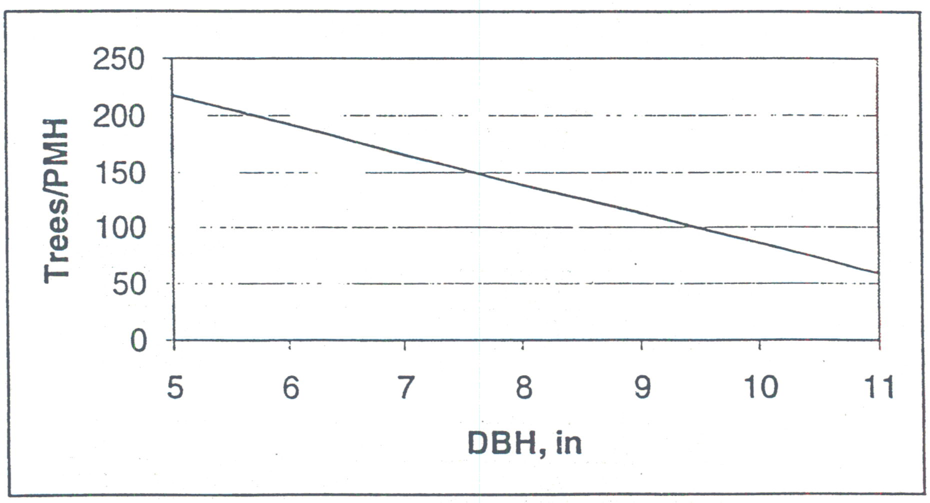

Figure 7. Delimbing productivity versus average DBH.

Delimbing Quality

On average, delimbing removed approximately 60-70 percent of the limbs, based on our visual estimates. Removal percentage was highly variable (Figure 8); on average, it decreased slightly as total basal area per grapple load increased (Table 2).

Several factors limited the delimbing quality. Handling multiple stems simultaneously obviously prevents the delimbing knives from fully removing branches between the stems, but three other aspects also contributed to the problem. The loader grappled stems two to four feet above the butts to prevent them from slipping out of the grapple. The delimber knives were another four 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 six to eight feet of each stem. The border trees, especially, had many low branches. Many of these limbs were dead, however, so they might easily be removed and broken into small chunks by the flail.

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 – also caused problems because they 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.

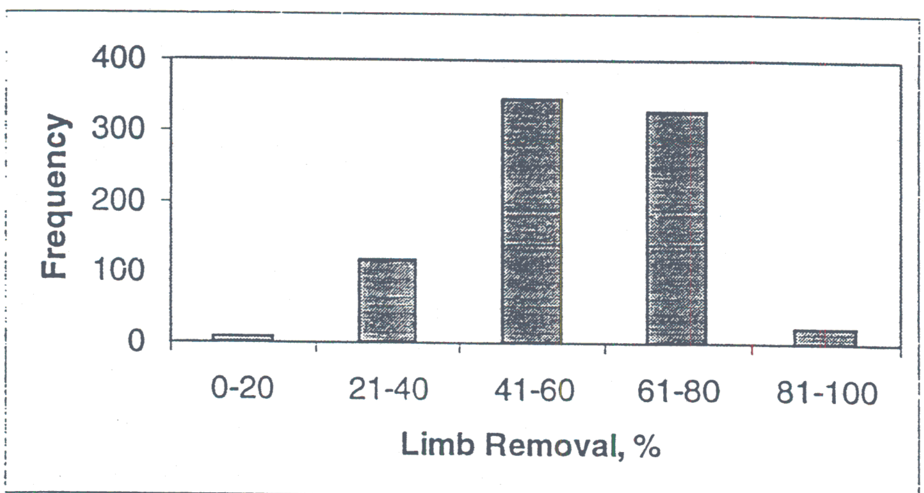

Figure 8. Distribution of delimbing quality.

DDC Production Rate

A complete table of DDC statistics is included in the appendix. 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. The weights were not significantly different, so conditions for a fair comparison of chipping rates were probably met.

On a per-load basis, chipping rate averaged 28.9 ODT per chipping hour and ranged from 21.1 to 37.4 ODT/hour (Figure 9). The production rate for delimbed stems was eight percent higher than that for whole trees, and the difference was significant (p = 0.02). Eight of the ten most productive loads were of delimbed trees, and eight of the ten least productive were of whole trees.

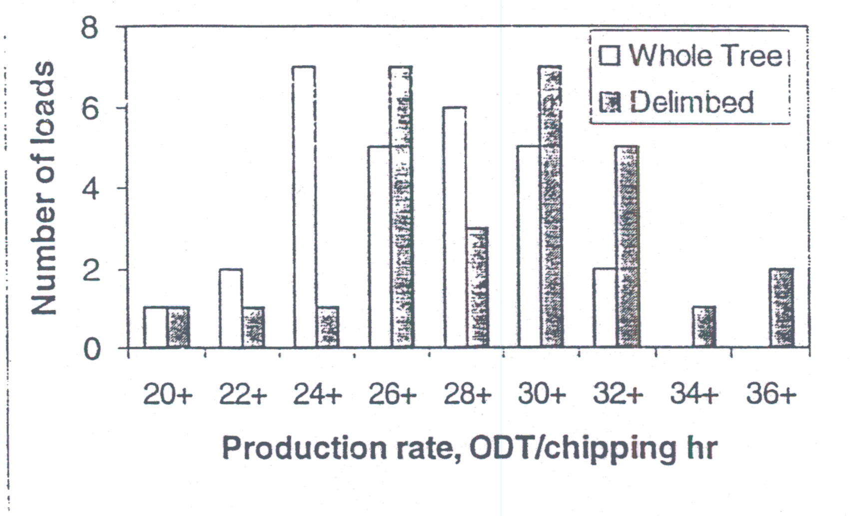

Figure 9. Distributions of chipping rates, for whole trees and delimbed trees.

The DDC operator fed 13% 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 a) the difficulties with handling stems that were broken during delimbing and subsequent decking, and b) 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 was doing a better job of indexing the stems as the trial progressed, and that the Volvo operator was stacking the delimbed trees in decks of less height, which seemed to reduce breakage.

DDC production rate decreased over the course of each day, for both delimbed and whole trees (Figure 10). The rate dropped by about half an oven-dry ton per hour, for each productive hour into the day. We'd guess that the decrease was caused mostly by operator fatigue, and that 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. Large border whole trees, however, appeared to be more difficult to chip due to their heavy branching. We developed a regression relationship that reflected the effects of time of day, type of tree and tree size:

$$\text{Chipping rate} = 16.6 - 0.63*\text{Hours} + 2.5*\text{Delimb} + 0.081*\text{Chip weight per tree}$$
$$R^2 = 0.31 \qquad n = 55$$

where Chipping rate = oven dry tons produced per chipping hour
Hours = chipping hours, at the start of the load, since the beginning of the shift
Delimb = a dummy variable with value of 1 for delimbed trees, 0 for whole trees
Chip weight per tree = oven dry 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 11.

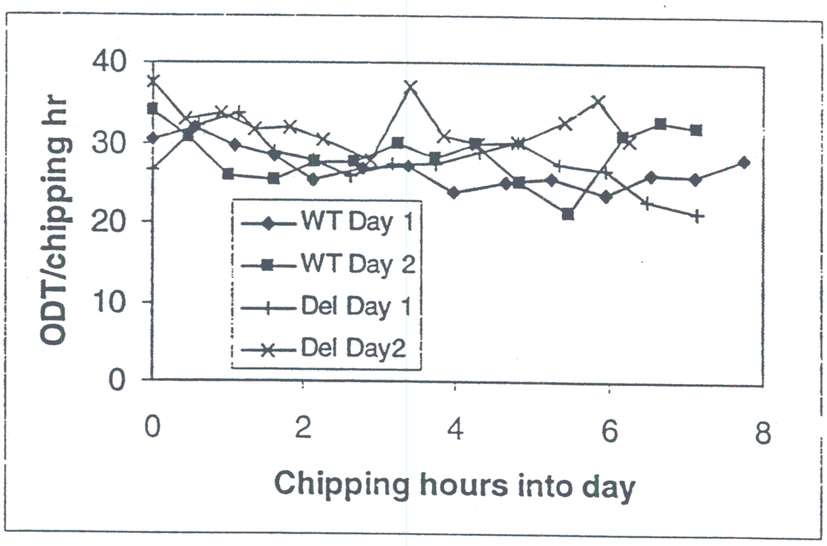

Figure 10. Chipping productivity for each load, versus chipping hours completed before beginning the load.

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 hour.) In retrospect, the roller could have been raised throughout the test of delimbed trees. The speeds of the delimber infeed rollers could also have been increased. Either of these changes would probably have increased chipping rate, although bark content might have gone up as well.

We only observed one move between landings, and it took 43 minutes from the time chipping stopped until the chipper was set up at the next landing.

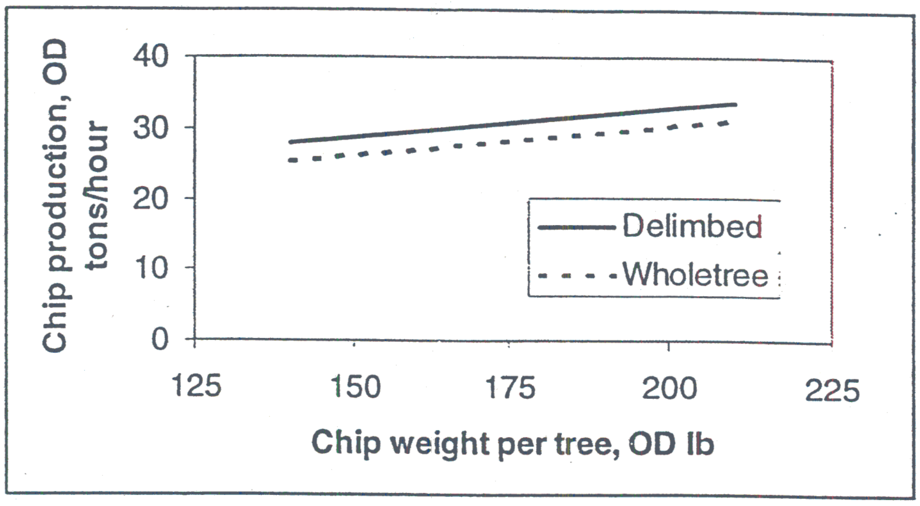

Figure 11. DDC production rate as effected by tree size and type of tree, after 4 hours of chipping.

Chip Quality

A complete table of chip quality values is included in the appendix. As shown in Figure 12, fewer of the chips from delimbed trees were acceptable; on average, 56% for delimbed versus 59% for whole trees ($p < 0.01$). The additional non-acceptable chips showed up as more oversize (12% vs. 10%, $p < 0.01$), overthick (15% vs. 14%, $p = 0.02$) and overlength chips (2.4% vs. 1.7%, $p = 0.04$). This might be due to the additional breakage of delimbed trees. There was essentially no difference in pins or fines contents. Bark contents averaged 2.6% for both delimbed and whole trees, so the higher production rate for delimbed trees did not come at the expense of an increase in bark.

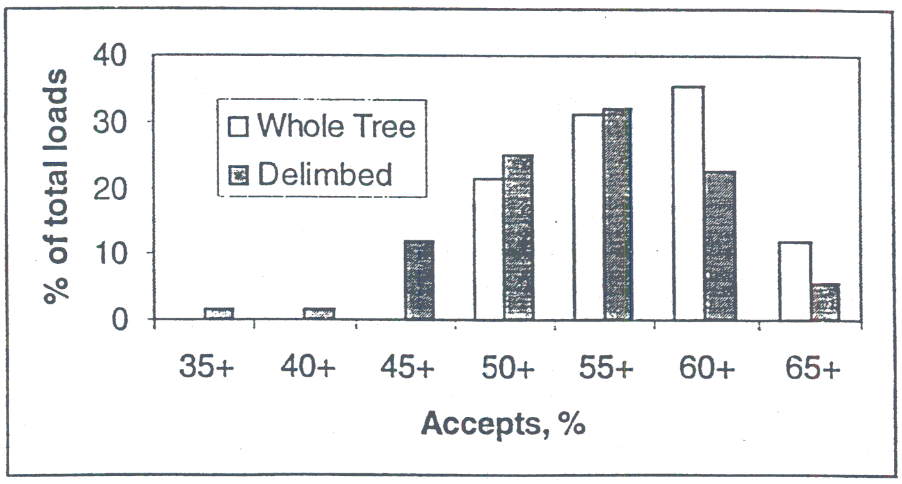

Figure 12. Distribution of chip accept percentages, for whole tree and delimbed loads.

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% subsample. Even for these, the variability was rather high. For example, the two values per van for moisture content and bark content are plotted in Figures 13 and 14, respectively. The absolute differences for moisture content and bark content averaged 2.1 and 1.1 percent, respectively.

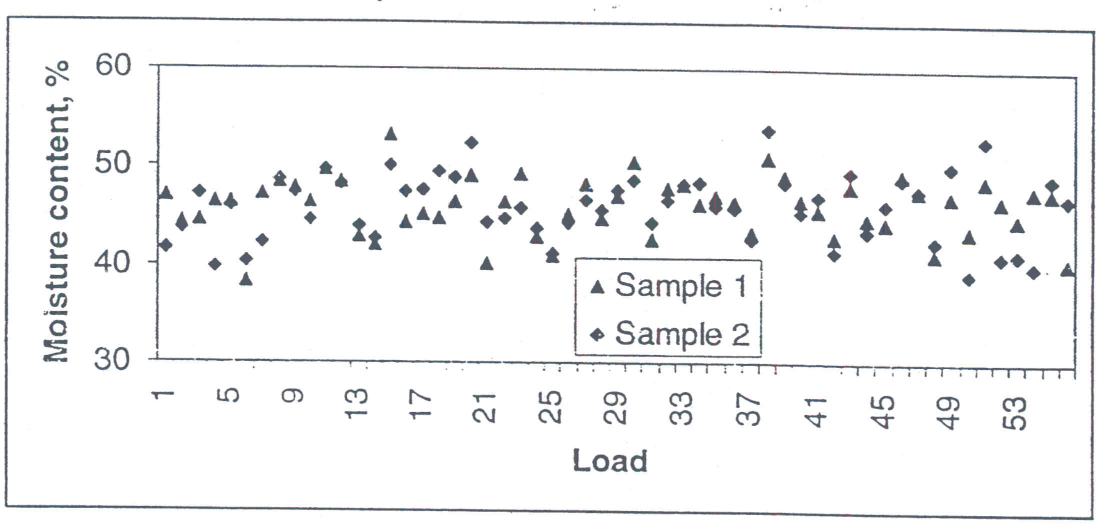

Figure 13. Moisture content results for two samples from each load.

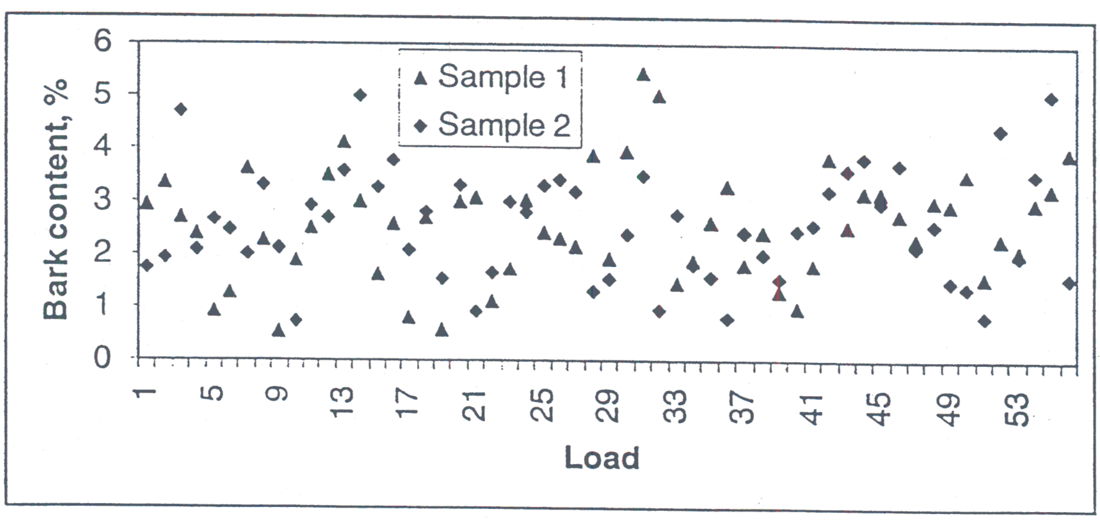

Figure 14. Bark content results for two samples from each load.

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 oven-dry percentage for the six loads where we had both (Figure 15). On average, the mill OD% was 3.5% higher than ours, but in the extreme case the values were quite different; 60% for the mill sample versus 48% for our sample. This indicates a need to collect many (or larger) samples to obtain good estimates of mean values.

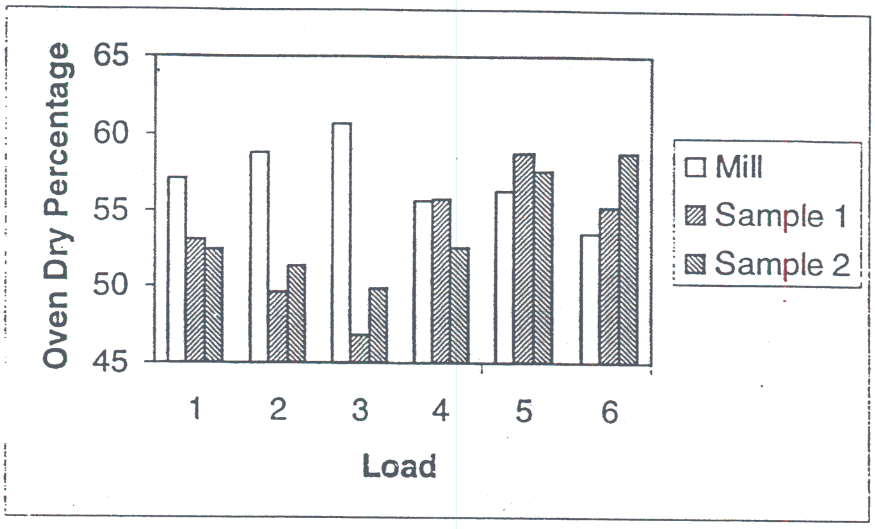

Figure 15. Comparison of oven dry percentages for mill samples and our samples, for six loads.

Fuel Consumption

Chipping delimbed trees consumed significantly less ($p = 0.012$) fuel per ODT than did chipping whole trees (Figure 16, Table 5). The difference of eight percent was essentially equal to the difference in production rate between the two materials. Consumption per chipping hour averaged 36.2 gallons, independent of production rate or tree type.

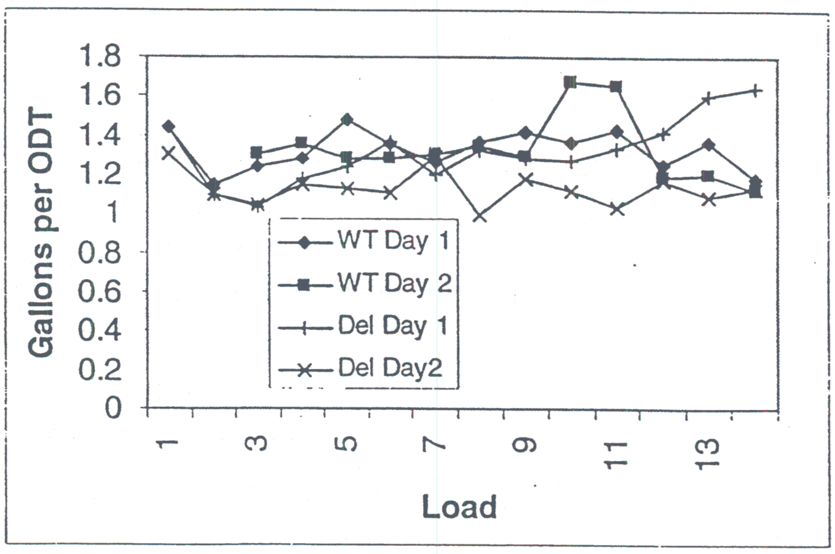

Figure 16. Fuel consumption per ton of chips, by load, for whole and delimbed trees.

Table 3. Peterson-Pacific DDC 5000 fuel consumption statistics.

	Mean	Std. Dev.	Range	Count
Fuel Consumption, gal/ODT				
Whole tree	1.33	0.14	1.11-1.68	26
Delimbed	1.22	0.16	1.00-1.64	28
Fuel Consumption, gal/chipping hour				
Whole tree	36.2	2.7	32.4-43.7	26
Delimbed	36.2	3.0	31.1-48.7	28

Chain Wear

Chain wear data is tabulated in the Appendix. There was very little weight loss from the chains: about two percent the first day and another four percent during the second day (Figure 17). Losses were essentially the same for the whole tree and delimbed conditions. With one exception, all chains retained all eight links after the two days. One outer link broke off a chain used on the delimbed trees; it was probably a defective link because the third link usually wears most rapidly and breaks first.

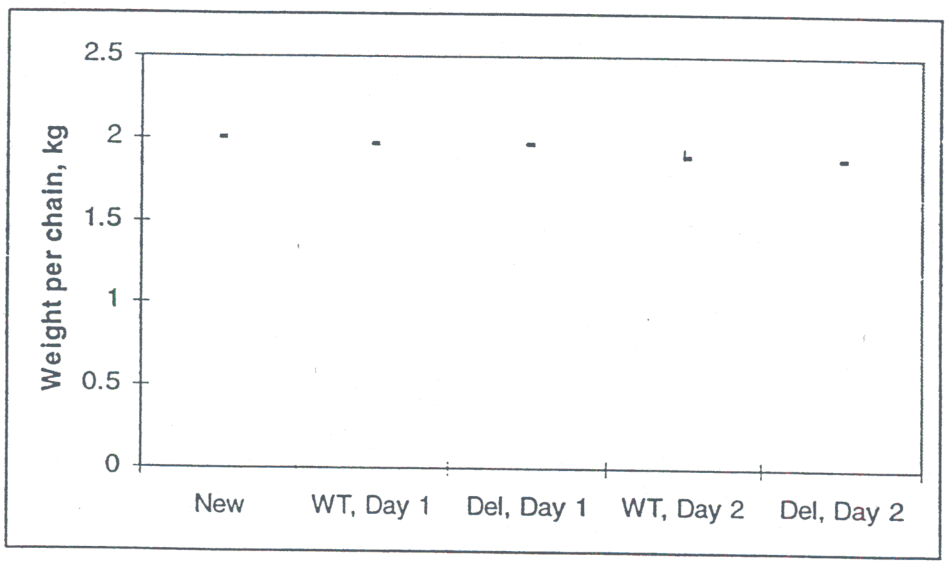

Figure 17. Chain weights after one and two days of use, for whole trees and delimbed trees. The vertical bars denote ranges; the dots are the means.

Thicknesses of the third links diminished by an average of 27% during the first day, and an additional 12% (of original thickness) during day two (Figure 18). The chains used with the delimbed trees lost a percent more thickness, but the difference was not significant.

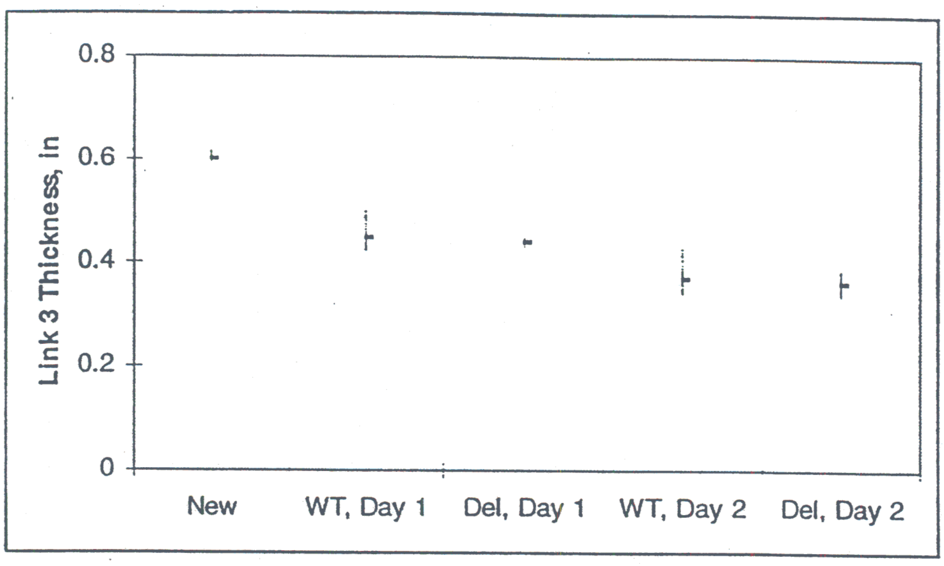

Figure 18. Chain link thicknesses after one and two days of use, for whole trees and delimbed trees. The vertical bars denote ranges; the dots are the means.

Delimber residues

The recorded average weights of delimber residue per tree for the eight sample batches of trees are shown in Figure 19. One value is over twice that of any other; we assumed that some element of this one point was erroneous and excluded it from the analysis. For the rest of the data, delimber residues averaged 31.7 green pounds per tree. We adjusted this upwards by 10 percent to account for the uncollected residues on the output end of the delimber.

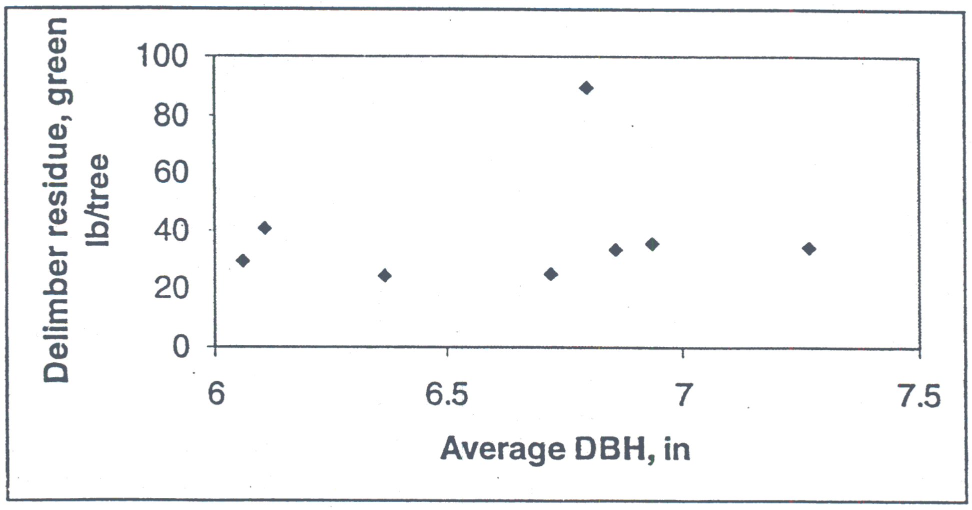

Figure 19. Recorded weight of delimber residue per tree, for eight batches of trees with between 76 and 166 trees per batch, by average eyeball-estimated diameter of the trees in the batch.

Chip and Residue Material

Figure 20 shows the distributions of weights per tree for each of the three whole tree loads and four delimbed loads for which residues were weighed. The averages for these loads are tabulated in Table 4.

Delimbing prior to flailing reduced bark discharge residues by approximately half. Other than the obvious differences in the amounts of bark discharge and delimber residues, the average values for whole trees and delimbed trees were not significantly different, but the number of observations was too small to detect small differences.

The pull-through delimber may remove some whitewood that the flail would not, lowering the recovery of high quality chips. It is not clear if pre-delimbing caused any loss of wood. 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 breakage due to multiple handling of the delimbed stems, but he delivered all of the broken pieces to the flail. (It took extra time to gather up the broken pieces.)

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 28 observed loads, the chip weight per tree was six pounds less for the delimbed trees, but the difference was only four percent of the total weight, and not significant.

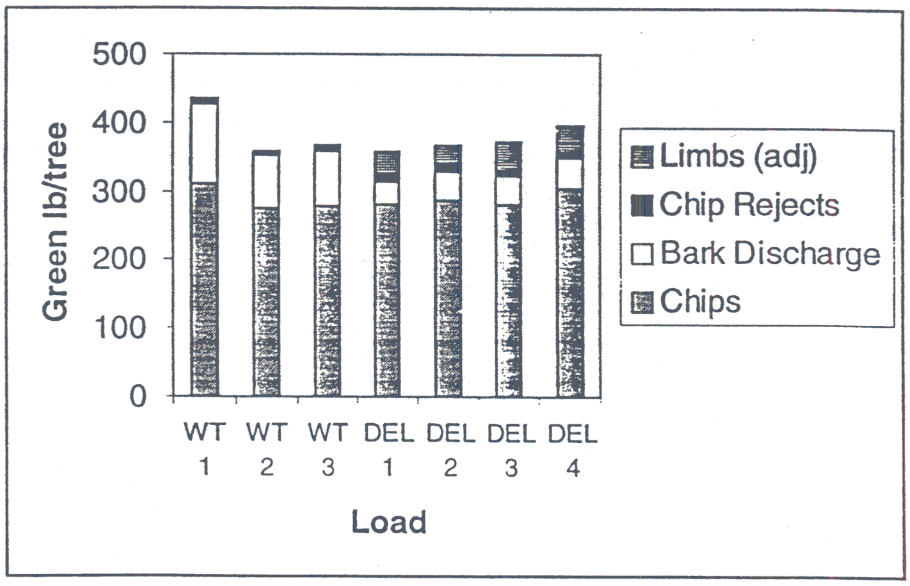

Figure 20. Weight per tree by category of material for whole trees and delimbed trees, based on one van load per observation.

Table 4. Green weight per tree, lb, based on one observation for each of the seven van loads for which residues were weighed.

Material	Whole trees	Delimbed trees
Chips	288.6	288.8
Residues		
Bark discharge	90.0	39.1
Chipper rejects	8.5	10.7
Delimber residues		34.9
Total residues	98.4	84.6
Total	387.0	373.4
# of observations	3	4

Economics

An economic comparison of the delimbed and whole tree cases was run for an average tree size (7" DBH, 162 OD lb of chips and 19 OD lb of limbs recovered at the delimber). Two scenarios were included for the delimber, one with the observed loader and production rate, and a second with a larger loader and twice the observed production rate (Table 5). Hourly costs were calculated with the machine rate approach (Miyata 1980), based on year 2000 purchase prices for current equipment models. The hourly costs of the Volvo and Cat loaders were included with those of the DDC, as the DDC limits the loaders' production rates. The calculated DDC production rates per chipping hour were reduced by five percent to adjust for productive delays such as 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.

Table 5. Costs for delimbing prior to processing versus processing whole trees.

	Whole Tree	Delimbed – observed	Delimbed – w/large excavator
Purchase prices, $1000			
Danzco PTH		27	27
Link Belt 2700		160	
Link Belt 3400			210
Peterson Pacific DDC 5000	400	400	400
Volvo L150	270	270	270
Cat 966	240	240	240
$/PMH			
Delimb		79	93
Process with DDC	374	374	374
Productivity, ODT/PMH			
Delimb		13.4	26.7
Process with DDC	25.9	28.3	28.3
Cost, $/ODT of chips			
Delimb		5.9	3.5
Process with DDC	14.5	13.3	13.3
Total	14.5	19.2	16.7

Predelimbing increases the productivity of the DDC and therefore reduces the DDC cost per ton. The cost of 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, it is more likely that the tons of chips grown and to be harvested each year is 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 breakeven differential value for the limbs can be found from:

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

where: Differential = breakeven 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 breakeven differential is about \$40/ODT of limbs. For the larger loader and higher productivity, the breakeven would only be about \$19/ODT of limbs, which may not be an unreasonable amount. Of course, the costs of comminuting and transporting the limbs must be considered in a complete analysis.

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 old John Deere 743 harvester could knock off tops at a preset diameter, e.g. 2", 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 using a ramp so the tops would slide laterally away from the delimber, or if the tops were removed by 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.

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

The pull-through delimber could process multiple stems simultaneously; an average of 3.5 stems per pull in the trial. In this mode, the delimber removed about two-thirds of the limbs from the hybrid cottonwoods, and these 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 loader was too small for the task. A larger loader might bring productivity up to near that of the DDC.

The DDC processed the delimbed trees 8% faster than whole trees, and might be able to increase that rate somewhat with adjustments to the infeed rollers. Fuel usage per ton was reduced by the same percentage; fuel consumption per chipping hour was approximately constant. 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 loader with the delimber. The combination might be economical if a) the value differential for recovered limbs was high enough and/or b) the delimber could be integrated into the flail/chipper so that the separate feed loader could be eliminated.

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Appendix

Table A1. Danzco delimber productivity statistics.

Variable	Mean	Std. Dev.	Range	n
Trees	3.50	0.84	1-6	826
DBH, in	6.49	0.85	4.2-11.0	826
BA, in2	115.	26.	28-205	826
Removal class	3.29	0.81	1-5	821
Cycle elements, cmin/grapple load				
Pick	38.5	17.4	0-141	826
Limb	37.3	17.6	12-171	826
Deck	22.5	8.0	0-57	826
Move	17.9	5.7	0-46	826
Other	2.0	17.3	0-802	826

Table A2. Peterson-Pacific DDC 5000 productivity statistics.

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

Table A3. Weight per tree by type of material.

Variable, green lb per tree	Mean	Std. Dev.	Range	n
Chips				
Whole tree	289.	19.	276-311	3
Delimbed	289.	11.	281-305	4
Bark discharge				
Whole tree	90.0	22.3	76-116	3
Delimbed	39.1	5.5	31-44	4
Chipper rejects				
Whole tree	8.5	0.9	8-9	3
Delimbed	10.7	1.5	8-12	4
Limbs (adjusted)				
Whole tree	0			3
Delimbed	34.9	4.8	29-39	4
Total residues				
Whole tree	98.4	23.1	83-125	3
Delimbed	84.6	7.7	75-91	4
Total weight				
Whole tree	387.	42.	359-436	3
Delimbed	373.	16.	357-396	4

Table A4. Chip quality and size distribution statistics.

Variable	Mean	Std. Dev.	Range	n
Moisture, %				
Whole tree	45.9	3.0	38-54	56
Delimbed	45.9	3.3	39-53	56
Bark, %				
Whole tree	2.50	1.12	0.5-5.5	56
Delimbed	2.61	0.98	0.6-5.1	56
3/8" dia. Accepts, %				
Whole tree	59.5	4.6	51-67	56
Delimbed	55.8	6.1	39-68	53
1-3/4" dia. Overlength, %				
Whole tree	1.7	1.6	0-7	56
Delimbed	2.4	2.2	0-10	53
8 mm slot Oversize, %				
Whole tree	9.9	3.0	2-16	56
Delimbed	11.8	4.0	4-24	53
6 mm slot Overthick, %				
Whole tree	13.8	2.5	8-20	56
Delimbed	15.0	2.9	7-21	53
3/16" dia. Pins, %				
Whole tree	12.6	2.8	8-20	56
Delimbed	12.2	3.3	6-24	53
Fines, %				
Whole tree	2.6	1.3	0-7	56
Delimbed	2.7	2.1	0-15	53

Table A5. Magnitudes of the differences between chip quality and size distribution values for the two samples taken from each van load.

Descriptive Statistics

	Mean	Std. Dev.	Std. Error	Count	Minimum	Maximum	# Missing
DelMC%	2.13	1.84	.25	56	.01	7.75	56
DelBark%	1.14	.79	.11	56	.06	4.08	56
DelOverlength	1.75	1.90	.26	53	0.00	8.69	59
DelOversize	3.13	2.65	.36	53	.02	13.15	59
DelOverthick	2.55	1.87	.26	53	.01	8.67	59
DelAccepts	3.07	2.74	.38	53	.07	11.14	59
DelPins	1.80	1.59	.22	53	.04	6.19	59
DelFines	1.00	.87	.12	53	.02	3.90	59

Table A6. Chain wear statistics.

Thickness of chain link #3 from outer end, in					
	New	WT, Day 1	Del, Day 1	WT, Day 2	Del, Day 2
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
% of new	100	74.5	72.7	61.4	60.2
Chain Weight, kg per chain					
maximum				1.95	1.95
minimum				1.87	1.70
average	1.99	1.96	1.96	1.89	1.87
% of new	100	98.2	98.2	94.6	93.9