COMPARISON OF MECHANIZED SYSTEMS FORTHINNING PONDEROSAPINEAND MIXEDCONIFERSTANDS

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ABSTRACT

Three systems for thinning pine plantations and naturally-regenerated stands were studied. All three produced small sawlogs and fuel chips. The whole-tree system consisted of a feller buncher, skidder, stroke processor, loader, and chipper. The cut-to-length system included a harvester, forwarder, loader, and chipper. A hybrid system combined a feller buncher, harvester, skidders, loader, and chipper. Time-motion study data were analyzed to predict cost per unit volume. The cut-to-length system had higher costs and yielded less fuel than the other systems. In plantations, the hybrid system was least expensive, while the whole-tree system was cheaper in the natural stands. The harvesters were capable of handling larger trees in the natural stands, and could remove limbs from the plantation pines, up to a limit. The cut-to-length system could operate on the steep and broken terrain included in the study.

Many concerns must be addressed when implementing ecosystem management: maintenance and enhancement of a diversity of stand structures and plant species, cycling ofnutrients, maintenance of soil structure, porosity and organic matter, conservation of habitat for fauna, reduction of the risk of wildfire, and the ability to extract forest products.

The whole-tree (WT) methods presently used in California to harvest small trees have several potential drawbacks. They rely on mechanical felling and bunching and whole tree skidding, and therefore remove most of the above-ground biomass to the roadside. Skidder travel tends to sweep duff and litter from trails, exposing bare mineral soil to possible compaction and disturbance, and skidded loads may damage residual trees. Past studies have shown higher damage to smaller trees, which should be retained if a diverse stand structure is desired.

Cut-to-length (CTL) systems may remedy these problems. Harvesters leave limbs and tops in the woods, retaining nutrients and organic matter on the site. Limbs and tops can be placed on trails to provide a mat for equipment travel, and the forwarders used to transport the short lengths carry the wood off of the ground, reducing the potential for adverse soil impacts. The short length of a forwarder translates into less potential for stand damage.

CTL systems have potential drawbacks as well, especially for conditions in California's Sierra Nevada region. Harvesters may not be able to remove the larger limbs that are characteristic of ponderosa pine in open-grown plantations, or to handle the taller trees found on higher quality sites. Forwarders have limited slope capabilities and may not be able to operate on a high percentage of the Sierran terrain. Less wood fuel is produced than with a WT system, and residual fuel loadings are higher than after WT harvesting.

Several CTL studies have been conducted in North America (e.g., 2,9,12,15), but only a few in ponderosa pine. McNeel and Rutherford (11) observed a CTL system logging naturally regenerated interior west coast stands that included some ponderosa pine. The diameter at breast height (DBH) aver-

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TABLE I. -Stand characteristics.

	Plantation	Natural stand
Species	Pinus ponderosa	Abies concolor, Calocedms decurrens, Pinus lambertiana, Pinus ponderosa
Average age (range) (yr.)	35	75 (40-100+)
Reserve stand prescription		Enhance habitat for spotted owl
Basal area (ft.^{2}/acre)	120	150
Trees/acre	75	120
Other reserv specs	All non-pine trees Brush islands for habitat	All live trees > 18" DBH All snags > 16" DBH Patches of saplings as wildlife screens
Removals		
Merchantable		
MBF/acre	4.5	3
Trees/acre	75	45
Avg. DBH (in.)	12	13
Biomass (excluding tops)		
Type	Small trees	Small live trees, dead, cull
Pieces/acre	3	95
Avg. DBH (in.)		8

aged 9 inches; maximum tree height was about 60 feet; and slopes were 10 percent or less. Barbour et al. (1) reported on harvesters working in fire-origin mixed conifer stands on the Colville National Forest in Washington, on gentle terrain and with small trees (6- to 9-in. average DBH). None of these indicated how CTL equipment would perform in conditions in the Sierra region: large limbs on plantation ponderosa, trees up to 100 feet tall, and steep and broken terrain.

Comparative studies of CTL and other systems have been conducted. Blinn et al. (3) simulated three hardwood harvesting systems: chain saw and forwarder CTL, chain saw and cable skidder tree-length, and feller/buncher and grapple skidder tree-length. CTL had the highest present worth per unit of investment. Holtzscher and Lanford (8) simulated three CTL systems for thinning pine plantations; those with a feller/buncher and processor or felleribuncher and chain saws were cheaper than a system with a single-grip harvester. Three studies compared CTL and WT systems in eastern Canada. Gingras (5) found CTL costs to be comparable or lower, in areas that required considerable travel between cut blocks. In contrast, the two other studies found WT to be 15 to 30 percent cheaper (6,7). Lanford and Stokes (10) also compared CTL and WT systems, for thinning young pine plantations. Although WT was less expensive during the actual study, projected costs were essentially identical for the two systems. It is apparent that comparative performance is dependent on the situation.

To evaluate harvesting systems under California conditions, we studied three systems for thinning pine plantations and naturally regenerated stands on the Stanislaus National Forest. Several researchers are investigating soil impacts, fuel loading, mechanical damage to residual trees, bark beetle activity, and long-term stand growth; results will be reported at a later date. This paper focuses on harvest costs, product recovery, and physical feasibility of the harvesting systems.

Approach

Harvest systems

All three systems produced small sawlogs and biomass (fuel) chips. No sorting of sawlogs was required as all were delivered to the same mill.

The WT system included a Timbco T420 feller buncher with shear, Timberjack 450B and Caterpillar 528 grapple skidders, Timberjack 90 stroke delimber/processor, Prentice 610 loader, and Morbark 60/36 drum chipper.[1] All trees were felled in one pass, and the merchantable ones (10 in. DBH) were piled separately from the biomass. Merchantable trees were skidded hot, i.e., with no separating time buffer, to the processor at the landing. The processor decked sawlogs and piled tops for later chipping. Most limbs were returned to the woods by the skidders, but larger ones in the plantation were piled for chipping. After all sawlogs were loaded out, the chipper moved in, and the biomass was skidded to the chipper.

The CTL system included a Timberjack 1270 harvester with 762B head, Timberjack 1010 forwarder, loader, and chipper. The harvester delimbed and bucked sawlogs from the merchantable trees. It also delimbed and bucked the biomass trees and biomass logs from the tops of the merchantable trees, down to 2 inches in diameter. The forwarder usually carried a single product — sawlogs or biomass logs — in any one load and cold-decked them separately. Little prepared room was needed for decking or subsequent loading; material was decked alongside main trails and roads and in landings. Chipping required a skidder to move biomass from the decks.

The hybrid (HYB) system blended WT and CTL. Merchantable trees were processed in the stand, but sawlogs and biomass bunches were skidded rather than forwarded. In the natural stands, a Timbco 420 feller buncher cut the biomass trees. An Equipment Repair EP200 harvester head on a Timbco T435 carrier then felled merchantable trees, delimbing and bucking long sawlogs (up to 33 ft.). It placed unlimbed tops on the biomass piles left by the feller buncher. In the plantation, the harvester felled all the trees because there were few biomass stems, so the biomass consisted mainly of tops from merchantable trees. Felling, sawlog skidding, and biomass skidding were segregated and carried out in that order. All material was skidded hot to the loader or chipper.

Stands

The systems were tested in two stands, a 35-year-old ponderosa pine plantation (40 acres total), and a mixed conifer stand that had been partially logged by railroad in the 1940s and had naturally regenerated (80 acres total). Characteristics of the stands are listed in **Table 1**, and diameter distributions are displayed in **Figures 1** and 2. Two replicate blocks were delineated in each stand type, and each block was divided into four units, one assigned at random to each harvest system. The remaining units

[1] The machines evaluated represent classes of equipment. Mention of trade name or model does not constitute an endorsement of a particular make.

were designated as controls for environmental impact studies.

The open-grown plantation pines were mostly under 18 inches DBH, but some had limbs over 4 inches in diameter, and the limbs commonly occurred in whorls of four or five. Large limbs were found almost down to the stump. Pines in the natural stands had smaller branches due to higher stand density.

Harvesting was carried out from May 2 through June 7, 1994. Essentially all skidding and forwarding was on favorable grades, i.e., loaded downhill, and distances ranged up to 1,000 feet. Slopes in the plantation were 25 percent or less; those in the mixed conifer blocks were up to 40 percent.

Data collection

We collected time-motion data on all stump-to-truck activities. Only data on operators with one or more years of experience were included in our analysis. Productive cycle time elements and other variables are defined in the **Appendix.** For felling, harvesting, and processing, tree DBH was estimated by eye, as were travel distances for felling and harvesting. Skidding and forwarding distances were estimated with prelocated markers. Numbers of pieces were counted for the sawlog and chip loads that were time' studied, and scale volume per load or weight per van was used to calculate average log volume or average biomass piece weight, respectively. Productivity relationships were developed from the time-motion cycle data, via regression analysis. A few productive delays were calculated on a time per load basis; all others were estimated as an additional percentage of productive cycle time and segregated by system and stand type where appropriate.

We tallied all removal trees by DBH, and sampled heights and diameters in each stand to develop local height-diameter relationships. Estimates of merchantable volume were made with the diameter tallies, height relationships, and tree volume equations (16). The weight of biomass in the non-merchantable trees and in tops and limbs of the merchantable trees were estimated using tabular data (14). All sawlogs were scaled at the mill, and weights and moisture contents of biomass chip vans were recorded. These data were used to calculate product recoveries for the three systems.

Results and discussion

Product recovery and characteristics

Product recovery percentages, biomass-to-sawlog ratios, and average sawlog volumes are listed **in Table 2.** The CTL system recovered more sawlog volume than the other systems. This may be due to the lack of breakage during forwarding, compared to skidding. The recovery fractions should be considered in a relative sense. Some are higher than one, but this is probably due to ocular underestimates of diameters and therefore volumes of the cut trees. The bias was considered to be consistent across the systems.

There were marked differences between the three systems in biomass yield, and the ratio of biomass to sawlogs. These reflected the CTL system's removal in the woods of all limbs and tops from biomass logs, and the hybrid's removal of limbs from sawlogs. Overall recovery ratios followed the same trend as for biomass, although the overall fractions varied less because the low biomass yields for the CTL system were partially offset by higher sawlog yields.

CTL sawlogs averaged approximately half the volume of those for the other systems due to their shorter lengths. The larger natural stand trees yielded bigger logs on average, and the large numbers of small and dead trees resulted in higher

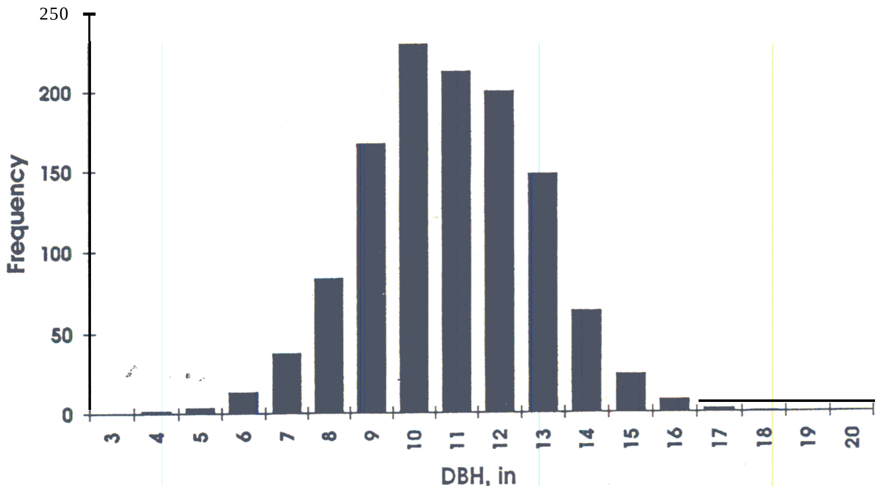

Figure 1. — Diameter distribution for the plantation. All trees were alive.

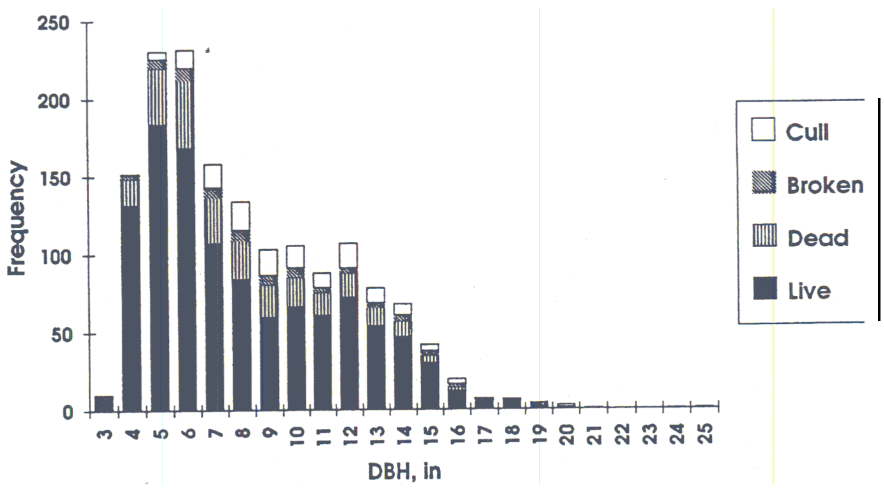

Figure 2. — Diameter distribution for the natural stand, by type of material.

TABLE 2. -Product recovery data fir the three harvesting systems.

	WT	HYB	CTL
Sawlogs (MBF Delivered/MBF Cut)			
Natural stand	1.10	0 95	I 13
Plantation	0.80	0.86	1.09
Biomass (BDT Fuel Delivered/BDT Residues Cut)			
Natural stand	0.68	0 63	0 48
Plantation	0.72	0.57	0.27
Sawlogs + biomass (BDT Delivered/BDT Cut)			
Natural stand	0.80	0.72	0.67
Plantation	0.76	0.71	0.60
Ratio of biomass to sawlogs (BDT/gross MBF)			
Natural stand	4.35	5.11	2.57
Plantation	2.21	1.89	0.98
Average sawlog volume (gross BF)			
Natural stand	65.8	63.0	30.4
Plantation	56.7	52.3	27.0

TABLE 3. — Machine replacement prices and hourly costs including labor.

Machine	Purchase price	Hourly cost
	($)	($/SH)
Timbco T420 w/20-in. shear	240,000	70
Timbco T435 w/EP200 harvester	370,000	96
Timberjack 450B skidder	160,000	58
Timbejack 90 processor	270,000	78
Timbejack 1270 w/762B harvester	460,000	123
Timberjack1010 forwarder	290,000	86
Prentice 6 10 loader	340,000	92
Prentice 325 loader	200,000	62
Morbark 60/36 chipper	260,000	89
Log truck, chip truck		50

[a] SH = scheduled hour.

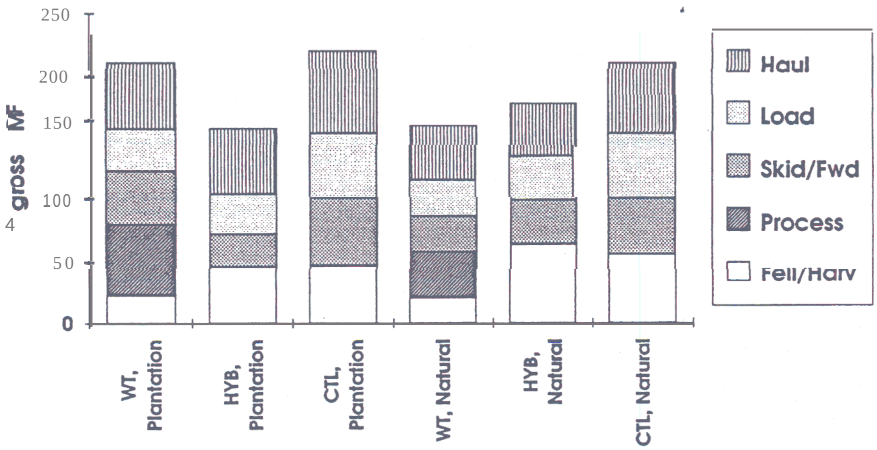

Figure 3. — Stump-to-mill costs for sawlogs.

ratios of biomass to sawlogs than in the plantation.

HARVESTING COSTS

To compare economics of the systems, a standard set of conditions was chosen for each stand type. Average pieces per acre and tree sizes from **Table 1** were used. Average skidding/forwarding distance was set at 400 feet and slope at 15 percent. Harvesting cycle time relationships, listed in the **Appendix,** were developed for each stump-to-truck activity. Production rates at maximum utilization were calculated from these relationships, for the biomass component and sawlog component. For hot activities, the numbers of machines were balanced to give minimum costs, although each system was limited to a single processor, loader, and chipper. Observed average times for truck travel for a 40-mile one-way haul including unloading were combined with predicted loading times to give productive hauling time per load. Observed averages were used for truck load volumes and chip van weights.

The machine rate approach (13) was used to calculate hourly costs for each piece of equipment **(Table 3). Key** assumptions included current replacement costs for equipment (or for current similar models), 20 percent salvage value, life of 5 years, 2,000 scheduled hours per year, and maximum utilization rates of 65 percent. Maintenance and repair percentages and supply and expense (S&E) costs were taken from a study by Brinker et al. (4), and S&E costs were adjusted for inflation. A labor rate of $12 per scheduled hour (SH) was assumed, plus 50 percent loading for benefits and other labor overhead. For trucking, a flat rate of $50 per scheduled hour was assumed, and utilization was set at 90 percent.

Hourly costs and production rates were combined to give total dollars per acre for each activity and product. The costs allocated to the biomass were incremental as much as possible, i.e., felling of non-merchantable trees, skidding or forwarding of biomass, and all chipping and chip hauling. The costs of handling tops by the harvesters, WT skidding of tops on merchantable trees, and decking of tops by the WT processor were not easy to separate and were therefore assigned to the sawlogs. The total dollars for sawlogs and for biomass were divided by the total amount of product to give costs per gross thousand board feet (MBF) for the sawlogs (Fig. 3) and costs per bone dry ton (BDT) for the biomass (Fig. 4).

In the plantation, the HYB system was least expensive. The harvester efficiently felled all material because there were so few biomass trees. The WT system had high processing costs, due to the large limbs, ability to handle only one tree per cycle, and the considerable time spent decking large tops for chipping. The processor was slower than the skidder, which increased skidding cost. It was less productive than either of the harvesters. For WT biomass, chipping limbs accumulated at the landing increased the costs of chipping and skidding. The CTL harvester was more productive than the HYB harvester, but also more costly per hour. Forwarding was twice as expensive as skidding for sawlogs, and several times as costly for biomass, due to the smaller CTL piece size. CTL hauling was more expensive because of the heavier trailer used for the shorter logs.

WT was cheapest in the natural stand. The processor and chipper were more productive than in the plantation, decreasing the costs for these activities and for the associated skidding. As in the plantation and for the same reasons, CTL was costlier than either the WT or HYB methods.

Harvesting costs could be reduced. The loader was oversized; a well-matched machine is expected to reduce loading costs by a third. WT chipping costs in the plantation could be reduced by skidding all limbs from processing back into the stand. Harvesters and processors with higher delimbing forces might reduce delimbing times for larger plantation trees. A larger forwarder would reduce travel distance per unit of material and speed up travel on the broken terrain. Balance between the harvester and forwarder could be obtained by working the least productive of the two for more hours. A lighter short log trailer would reduce hauling costs for the CTL logs, and setout trailers would eliminate the loader cost, at some additional forwarding cost if the forwarder was more limiting than the harvester.

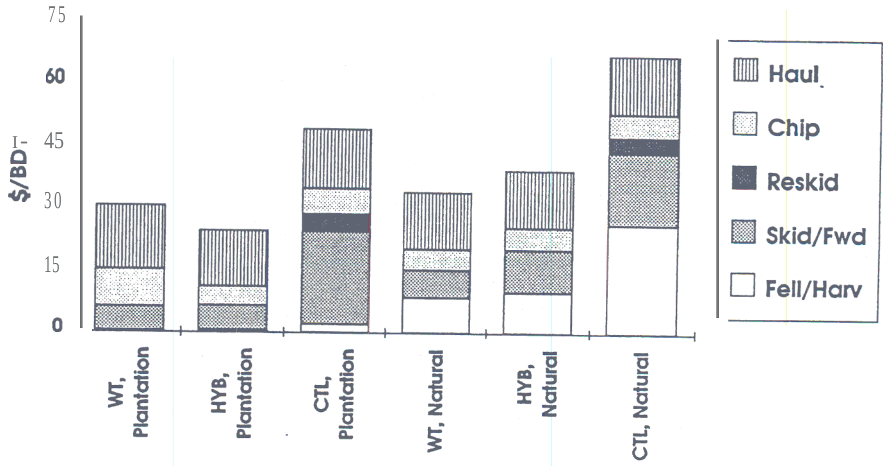

Figure 4. — Stump-to-mill costs for biomass fuel.

Physical limitations

WT. — The feller bunchers and the skidders were able to negotiate the terrain on all the study units. With the exception of a single 20-inch DBH tree, bole diameter and tree weight did not exceed the feller buncher's limits. Although the stroke delimber was slow in the plantation, it removed all limbs without obvious delays or difficulty and with essentially no damage to the boles.

CTL. — Terrain was not too steep or broken for forwarding on any of the CTL units, but slopes over 10 percent did require trails that were directly downhill, resulting in longer travel distances than with skidding on similar terrain. The observed forwarding slope extremes while loaded were: 42 percent downhill, 23 percent uphill with' a full load, and 35 percent uphill with half a load.

No trees designated for harvest in the CTL units were too large for the harvester; the largest green trees were 18 inches DBH, and the largest snag was 25 inches DBH. The harvester could easily remove limbs up to 2.0 inches in diameter; multiple strokes were required for larger limbs, and those over 2.5 inches could not be removed. On a large-scale operation, a chain-saw operator might fell and delimb the trees with oversized limbs, working ahead of the harvester.

HYB. — The feller buncher, harvester, and skidders were able to negotiate the terrain on all units, and tree size did not pose a problem. The EP 200 head is capable of cutting trees up to 24 inches at the butt. By chance, the largest limbs found on the study were in one of the HYB plantation units. The EP 200 head was able to remove limbs smaller than 4.5 inches in diameter, using multiple strokes on the larger ones, but the aggressive feed roll teeth caused some degrade to the bole wood.

Summary and conclusions

In the natural stands, with their wider range of tree sizes and smaller branches, the WT system was least expensive because it handled fewer pieces from stump to landing and efficiently processed the naturally pruned trees. All delimbing was slower in the large-branched ponderosa pine plantations, but both harvesters were relatively more efficient than the stroke processor. The lower cost of processing with the harvester made the HYB system the least expensive in the plantation. The CTL system had the highest cost in both stand types, because of multiple handling of small pieces. Cost, however, is only one element of harvest system selection.

Questions about the physical feasibility of CTL equipment were answered. The Timberjack harvester could handle the largest trees encountered in the natural stands; some of these were 18 inches DBH and 100 feet tall. The largest limbs on plantation ponderosa pine could not be removed. The Timbco 435 with EP 200 harvester head could remove larger branches, but was slower than the Timberjack. For trees from older plantations, a chain saw or a more robust harvester will be required. The forwarder was able to operate on the steeper slopes and on broken terrain. These promising results indicate that CTL systems may be feasible in much of California, although careful layout will be required on steeper sites.

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Appendix. Harvesting Productivity Relationships

For each piece of equipment, cycle time elements and other variables are defined, then statistics and regression relationships are tabulated. For variables where only mean differences were significant, standard deviations are reported in the r^2 column in the relationships tables.

Table A1. — Feller/buncher, harvester, and processor variable definitions.

Cycle (centimmutes (cmin))	Time per accumulation of trees in the head = Move x MoveFrac + Fell
Move (cmin)	Time spent moving without a tree in the head
Dist (ft.)	Straight line distance traveled
Slope (%)	Fall line slope
MoveFrac	Fraction of cycles which include a Move
Fell (cmin)	Time to fell all trees in the accumulation, including moving with trees
DBH (in.)	Diameter at breast height of each tree
Trees	Number of trees and other pieces in the accumulation
Dead	1 = dead tree (snag), 0 = other material
Hybrid	1 = hybrid system, 0 = other system
TimePerTree (min.)	= Cycle x (1 + DelayFrac)/Trees/100
Harvester differences	
Cycle (cmin)	Time per tree = Move x MoveFrac + Fell + Process
Fell (cmin)	Time to fell a tree until it hits the ground, including moving with the tree
Process (cmin)	Time to delimb and buck, including placing the top in a biomass pile
Sawlogs	Number of sawlogs cut from a tree
Biologs	Number of biomass pieces cut from a tree
Plant	1 = plantation, 0 = natural stand
TimePerTree (min.)	= Cycle x (1 + DelayFrac)/100
Processor differences	
Cycle (cmin)	Time per processor grapple load = Process + MoveTops x MoveTopsFrac
Process (cmin)	Time to delimb and buck a grapple load, including decking sawlogs
Stems	Number of stems grappled
MoveTops (cmin)	Time to pile tops for chipping
MoveTopsFrac	Fraction of cycles which include a MoveTops
TimePerTree (min.)	= Cycle x (1 + DelayFrac)/Stems/100

Table A2. — Timbco T420 feller/buncher statistics.

Variable	Mean	Std. Dev.	Range	Obs.
Move (cmin)	57.5	52.6	7 to 480	522
Dist, plantation (ft.)	33.8	34.9	5 to 250	154
Dist, natural (ft.)	43.1	44.6	5 to 300	229
Slope (%)	13.6	9.6	0 to 35	518
MoveFrac, plantation	0.394			
MoveFrac, natural	0.130			
Fell (cmin)	65.0	38.1	4 to 341	3179
DBH (in.)	8.42	3.58	2 to 25	3132
Trees	1.52	0.87	1 to 5	3132
DelayFrac	0.0963			

Table A3. — Timbco T420 productivity relationships.

		r^2	Obs.
Trees, plantation	= 1	s = 0	385
Trees, natural	= 1.81 – 0.0664 × DBH + 3.64/DBH – 0.0058 × Slope – 0.27 × Hybrid – 0.10 × Dead	0.23	3071
Move	= 19.2 + 0.77904 × Dist + 35.0 × Hybrid	0.80	387
Fell, plantation	= 49.9	s = 24.6	392
Fell, natural	= 28.5 + 12.6 × Trees + 1.76 × DBH × Trees – 3.94 × Dead	0.23	2745

Table A4. — Timbco T435/EP200 harvester statistics.

Variable	Mean	Std. Dev.	Range	Obs.
Move (cmin)	67.8	59.1	10 to 375	296
Dist (ft.)	45.2	57.2	5 to 450	298
Slope (%)	13.5	7.1	0 to 35	1382
MoveFrac, plantation	0.207			
MoveFrac, natural	0.266			
Fell (cmin)	52.7	25.8	3 to 310	1318
DBH (in.)	11.9	2.5	3 to 20	1330
Sawlogs	1.14	0.37	0 to 3	1249
Biologs	1.01	0.10	1 to 2	1246
Process (cmin)	60.0	41.8	9 to 516	1238
DelayFrac, plantation	0.024			
DelayFrac, natural	0.182			

Table A5. — Timbco T435/EP200 productivity relationships.

		r^2	Obs.
Sawlogs	$= 0.761 + 0.00317 \times DBH^2 - 0.00105 \times DBH^2 \times Plant$	0.18	1187
Move	$= 51.6 + 1.01 \times Dist - 24.0 \times Plant - 0.494 \times Dist \times Plant$	0.78	298
Fell	$= 39.8 + 0.114 \times DBH^2 - 5.82 \times Plant$	0.08	1253
Process	$= 22.8 + 0.200 \times DBH^2 + 235.2 \times Plant - 44.1 \times DBH \times Plant + 2.03 \times DBH^2 \times Plant$	0.26	1156

Table A6. — Timberjack 1270 harvester statistics.

Variable	Mean	Std. Dev.	Range	Obs.
Move (cmin)	50.1	38.1	8 to 242	408
Dist, plantation (ft.)	13.5	14.0	1 to 100	205
Dist, natural (ft.)	17.0	15.3	5 to 100	203
Slope (%)	11.7	8.5	0 to 40	1775
MoveFrac, plantation	0.255			
MoveFrac, natural	0.207			
Fell (cmin)	28.0	14.3	3 to 193	1780
DBH (in.)	9.7	3.0	4 to 20	1725
Sawlogs	1.18	1.05	0 to 5	1811
Biologs	1.12	0.59	0 to 5	1809
Process (cmin)	33.0	25.2	3 to 317	1816
DelayFrac	0.029			

Table A7. — Timberjack 1270 productivity relationships.

		r^2	Obs.
Sawlogs	$= -0.99 + 0.227 \times DBH$	0.46	1802
Biologs	$= 1.24 + 0.330 \times Plant - 0.056 \times DBH \times Plant$	0.07	1801
Move	$= 24.1 + 1.13 \times Dist + 0.040 \times Dist \times Slope$	0.45	408
Fell	$= 13.1 + 1.15 \times DBH + 0.329 \times Slope$	0.04	1725
Process	$= 8.4 + 0.232 \times DBH^2 + 64.3 \times Plant - 15.0 \times DBH \times Plant + 0.818 \times DBH^2 \times Plant$	0.43	1804

Table A8. — Timberjack 90 processor statistics.

Variable	Mean	Std. Dev.	Range	Obs.
Process (cmin)	93.0	50.7	13 to 335	451
DBH (in.)	11.6	2.3	7 to 19	432
Sawlogs	1.11	0.34	0 to 3	443
Biologs	1.01	0.12	0 to 2	443
Stems, plantation	1	0	1 to 1	93
Stems, natural	1.21	0.47	1 to 4	336
MoveTops (cmin)	62.4	31.6	6 to 183	149
MoveTopsFrac				
Plantation	0.516			
Natural	0.281			
DelayFrac	0.169			

Table A9. — Timberjack 90 productivity relationships.

		r^2	Obs.
Sawlogs	$= 0.87 + 0.00158 \times DBH^2 + 0.000750 \times DBH^2 \times Plant$	0.12	429
Process	$= -77.1 + 3.8 \times DBH + 78.3 \times Sawlogs + 27.5 \times Stems + 25.5 \times Sawlogs \times Plant$	0.54	426
MoveTops			
Plantation	= 53.2	s = 32.0	49
Natural	= 66.8	s = 30.6	100

Table A10. — Forwarder and skidder variable definitions.

Cycle (cmin)	Time per forwarder load = Travel + Load + MoveWoods + Unload
Travel (cmin)	Sum of travel empty and travel loaded times
Dist (ft.)	One way slope distance from landing to center of the load accumulation area
Slope (%)	Average fall line slope over Dist
Trail	1 = travel on main trail, 0 = travel within stand
Load (cmin)	Sum of loading times per load
Sawlogs	Number of sawlogs collected for the load
Biologs	Number of biomass logs collected for the load
Logs	Total number of logs per load
MoveWoods (cmin)	Sum of moving times while partially loaded
DistRange (ft.)	Range of distance over which the load is accumulated (Dmax – Dmin)
Unload (cmin)	Time to unload all logs at the landing
LogWeight (green lb.)	Average log weight, from log load data, chip van weights and piece counts
LoadWeight (green tons)	LogWeight × Logs/2000
TimePerGreenTon (min.)	= Cycle × (1 + DelayFrac)/LoadWeight/100
Skidder differences	
Biomass	1 = biomass turn, 0 = WT merchantable or HYB sawlog turn
Cat	1 = Caterpillar 528, 0 = Timberjack 450B
Cycle (cmin)	Time per turn = TravelEmpty + Load + MoveWoods + TravelLoaded + Unload
TravelEmpty (cmin)	Time to travel from landing to first load point
TravelLoaded (cmin)	Time to travel to landing with the complete turn
TimePerLog (min.)	= Cycle × (1 + DelayFrac)/Logs/100

Table A11. — Timberjack 1010 forwarder statistics.

Variable	Mean	Std. Dev.	Range	Obs.
Travel (cmin)	992.8	419.2	347 to 2609	73
Dist (ft.)	676.	272.	10 to 1040	76
Slope (%)	12.3	8.5	0 to 30	76
Load (cmin)	1432.3	339.7	860 to 2371	55
Sawlogs	33.8	19.6	0 to 62	56
Biologs	34.8	39.3	0 to 133	56
Logs	68.5	24.4	31 to 141	56
MoveWoods, (cmin)	644.8	300.2	191 to 1365	55
DistRange (ft.)	228.	171.	50 to 950	56
Unload (cmin)	781.4	225.9	316 to 1433	57
LogWeight (green lb.)	348.	123.	160 to 484	55
LoadWeight (green tons)	10.79	2.38	5.36 to 15.37	55
DelayFrac	0.059			

Table A12. — Timberjack 1010 productivity relationships.

		r^2	Obs.
LoadWeight	$= 7.13 + 0.0105 \times LogWeight$	0.30	55
Logs	$= 122. - 0.155 \times LogWeight$	0.63	55
Travel	$= 153.0 + 0.920 \times Dist + 0.0122 \times Dist \times Slope - 0.422 \times Trail \times Dist$	0.58	71
Load	$= 642.5 + 12.0 \times Sawlogs + 10.7 \times Biologs$	0.52	55
MoveWoods	$= 458.9 + 0.808 \times DistRange$	0.21	55
Unload	$= 359.7 + 6.689 \times Sawlogs + 2.196 \times Biologs$	0.17	56

Table A13. — Grapple skidder (Timberjack 450B and Caterpillar 528) statistics.

Variable	Mean	Std. Dev.	Range	Obs.
TravelEmpty (cmin)	207.9	117.1	12 to 703	283
Dist (ft.)	560.	323.	20 to 1200	297
Slope (%)	12.1	7.6	0 to 30	292
Load (cmin)	92.5	77.1	5 to 436	288
Logs, biomass turns				
Timberjack	17.90	6.35	2 to 31	70
Cat 528	12.11	5.63	2 to 26	28
Logs, merch turns				
Hybrid	6.39	2.50	1 to 12	85
Wholetree	4.75	1.67	1 to 10	106
MoveWoods (cmin)	111.5	144.7	0 to 731	288
TravelLoaded (cmin)	174.3	97.1	11 to 516	290
Unload, (cmin)	73.5	74.9	2 to 386	242
DelayFrac				
Biomass turns	0.216			
Merch hybrid turns	0.154			
Merch WT turns	0.195			

Table A14. — Skidder productivity relationships.

		r^2	Obs.
TravelEmpty	= 45.7 + 0.222 × Dist + 0.00429 × Slope × Dist + 0.0397 × Cat × Dist	0.58	283
Load, biomass	= 80.6 + 4.33 × (1 – Plant) × Logs	0.16	94
Load, merch	= 31.3 + 6.03 × Logs + 0.178 × Slope × Logs – 23.6 × Plant	0.20	179
MoveWoods	= 6.4 + 14.7 × Logs - 6.30 × Biomass × Logs + 54.8 × Hybrid – 83.1 × Plant	0.23	279
TravelLoaded	= 40.8 + 0.221 × Dist + 0.0496 × Cat × Dist	0.58	283
Unload	= 120.5 (for merch hybrid turns, many of which were cold-decked)	s = 106.	77
	= 51.5 (for all other situations, hot)	s = 38.7	165

Table A15. — Loading and chipping variable definitions.

Load (cmin)	Time to load a grapple load of logs
Logs	Number of logs in the grapple
LogVol (BF)	Average gross volume per log
SwingVol (BF)	Gross volume per swing
ExchangeTruck (cmin)	Time to prepare and pull the loaded truck out, and move in and prepare the empty truck for loading
TiedownBunk (cmin)	For shortlog CTL loads, time to put binders on the first bunk of two
TimePerMBF (min.)	= {Load × (1 + DelayFrac)/VolPerSwing × 1000 + (ExchangeTruck + TiedownBunk)/LoadVolume,MBF}/100
Chipper Differences	
Chip	Time to chip a grapple load
BiologWeight (dry lb.)	Average weight per log
WtPerSwing (dry lb.)	Weight per swing, = BiologWeight × Logs
Slash (cmin)	Time to chip limbs from WT processing, or other small slash
TimePerDryTon (min.)	= {Chip × (1 + DelayFrac)/WtPerSwing × 2000 + (Slash + ExchangeTruck)/WeightPerVan, dry tons}/100

Table A16. — Prentice 610 loader statistics.

Variable	Mean	Std. Dev.	Range	Obs.
Load (cmin)	108.0	66.7	6 to 423	1234
Logs	2.11	1.74	1 to 10	1224
LogVol (BF)	49.0	16.9	26 to 76	1234
SwingVol (BF)	107.	103.	26 to 650	1224
ExchangeTruck (cmin)	865.	450.	391 to 2545	27
TiedownBunk (cmin)	591.3	610.4	197 to 1496	4
LoadVol (gross MBF)				
Wholetree or Hybrid	3.69	0.56	2.40 to 4.84	73
CTL	2.93	0.37	2.43 to 3.89	24
DelayFrac	0.098			

Table A17. — Morbark 60/36 chipper statistics.

Variable	Mean	Std. Dev.	Range	Obs.
Chip	42.2	20.9	4 to 208	2158
Logs	3.56	2.27	1 to 16	2148
BiologWeight (dry lb.)				
Plantation wholetree	289	63.	210 to 398	8
Plantation hybrid	193	57.	150 to 330	9
Natural, WT or hybrid	141	21.	111 to 188	29
CTL	84	8.	79 to 98	5
WtPerSwing (dry lb.)	533.	321.	79 to 2786	2059
Slash (cmin)	512.	1078.	0 to 4632	45
ExchangeTruck (cmin)	529.	250.	157 to 1051	22
WeightPerVan (dry tons)	12.8	1.4	8.8 to 18.1	85
(green tons)	(22.3)			
DelayFrac	0.038			

Table A18. — Loader and chipper productivity relationships

		r^2	Obs.
Loader			
Load	$= 35.1 + 36.1 \times Logs - 3.11 \times Logs^2 + 0.148 \times SwingVol + 12.8 \times Hybrid$	0.36	1224
Chipper			
Logs	$= 1.20 + 338./BiologWeight$	0.13	2059
WtPerSwing	$= 280. + 1.58 \times BiologWeight$	0.09	2059
Chip	$= 25.0 + 2.64 \times Logs + 0.0498 \times BiologWeight$	0.08	2059
Slash			
Plantation WT	= 2786	s = 1112.	7
All others	= 93.	s = 143.	38

For chipping, effective biomass piece weight was largest for the whole tree tops in the plantation, and next largest for the hybrid tops. The actual top weights were probably similar, but the large number of limbs left by the processor at the whole tree landings increased the effective weight because limbs were chipped but not included in the piece count. Because of the numerous limbs, time to chip WT slash averaged almost half an hour per van in the plantation.