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COMPARISON OF MECHANIZED SYSTEMS FOR THINNING PONDEROSA PINE AND MIXED CONIFER STANDS

by

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Summary: We studied three systems for thinning pine plantations and naturally-regenerated stands on the Stanislaus National Forest, California. 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 and harvester to produce bunches of small whole trees for fuel, and bunches of long delimbed sawlogs. The hybrid bunches were skidded to a landing where they were chipped or loaded. The cut-to-length system had higher costs per unit of material and yielded less fuel than the other systems. The cut-to-length system damaged fewer trees in the natural stand than the other systems, but damage levels were low for all systems. Other environmental impacts - on soil, fuel levels, insect activity and stand growth - are still being evaluated.

Keywords: Forest harvesting, equipment, ecosystem impacts

INTRODUCTION

Many current concerns must be addressed by individuals who are involved with implementing ecosystem management. Among these are the maintenance and enhancement of a diversity of stand structures and plant species, cycling of nutrients, 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.

Methods presently used in California to harvest small trees have several potential drawbacks. They generally rely on mechanical felling and bunching and whole tree skidding, and therefore remove most of the above-ground biomass to roadside. Skidders tend to sweep duff and litter from trails, exposing bare mineral soil to possible compaction and disturbance, and may damage residual trees because of the relatively long lengths of skidded whole trees. Past studies have shown higher damage to smaller trees which are important to retain if a diverse stand structure is desired.

Cut-to-length systems may remedy these problems. The harvesters can remove all or most of the limbs and tops in the woods, retaining nutrients and organic matter on site. The limbs and tops can be placed on the 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 loaded forwarder translates into less potential for damage to residual trees.

Cut-to-length systems have potential drawbacks as well. Harvesters may not be able to remove larger limbs and forwarders have limited slope capabilities. Values of sawlogs may be reduced and less wood fuel is produced than with a whole tree system. Fuel loadings are higher than after whole-tree harvesting.

In order to compare the many aspects of various harvesting systems, we studied three systems for thinning pine plantations and naturally-regenerated stands on the Stanislaus National Forest. Cooperators included Joe Martin Logging, individuals from three USDA Forest Service research stations (Pacific Northwest, Pacific Southwest, Southern), the Stanislaus National Forest and the University of California, Davis. FMG Timberjack provided the cut-to-length harvester and forwarder and operators. The research cooperators are investigating soil impacts, fuel loading, bark beetle activity and long-term stand growth, physical feasibility of the harvesting systems, harvest costs, product recovery, and mechanical damage to residual trees due to harvesting. This paper reports on the last four aspects. Data collection is still under way for most of the other areas, and results will be reported at a later date.

APPROACH

Harvest Systems

All three systems produced small sawlogs and biomass (fuel) chips, there being no local market for pulpwood or pulp chips. No sorting of sawlogs was required as all sizes and species were delivered to the same mill.

The whole tree (WT) system consisted of a Timbco T420 feller buncher with shear head, Timberjack 450B and Caterpillar 528 grapple skidders, a Timberjack 90 stroke delimber/processor, Prentice 610 loader, and Morbark 60/36 drum chipper. All trees were felled in one pass, with the merchantable ones, i.e. those larger than approximately 10" DBH, being piled separately from the biomass. On each unit, felling was completed before skidding began. Merchantable trees were skidded hot to the processor at the landing. The processor decked the sawlogs and piled the 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 bunches were skidded hot to the chipper. The skidders also moved the piled tops and limbs to be chipped.

The cut-to-length (CTL) system included an FMG Timberjack 1270 harvester with 762B head, FMG Timberjack 1010 forwarder, loader and chipper. The harvester delimbed and bucked the sawlogs from the merchantable trees. It also delimbed and bucked the biomass trees and biomass logs from the tops of the merchantable trees, up to about two inches in diameter. The sawlogs and biomass logs were placed separately, sometimes in discrete piles and more frequently in sparse windrows along the harvester/forwarder trails. The forwarder usually carryied a single product in any one load, but combined the sawlogs and biomass logs on cleanup loads. The sawlogs and biomass logs were cold-decked separately. Little room was needed for loading or decking. Material was decked alongside roads, along a main trail, and in landings, depending on available space. The subsequent chipping operation required a skidder to move material from the biomass decks to the chipper. Though the loader and chipper were used at the landing, the forwarder had the capability to load setout trailers with sawlogs, and with biomass logs to be chipped at the mill.

The hybrid (HYB) system had some of the characteristics of the whole tree system, and some of the CTL system. Merchantable trees were processed in the stand, but the sawlogs and biomass bunches were skidded rather than forwarded. In the natural stands, the system combined a Timbco 420 feller buncher and an Equipment Repair EP200 harvester head on a Timbco T435 carrier. The feller buncher cut and bunched the biomass trees. The harvester followed in a second pass, felling the merchantable trees, delimbing and bucking long sawlogs (up to 33 feet) and bunching them. It then placed the unlimbed tops on the biomass piles created by the feller buncher. In the plantation, the harvester carried out all the felling activity because there were not enough biomass stems per acre to justify a first pass with the feller buncher. Therefore, the biomass bunches consisted mainly of the unlimbed tops from the merchantable trees. As with the whole tree system, the felling, sawlog skidding and biomass skidding were segregated and carried out in that order. Sawlogs were skidded hot to the loader, although they could have been decked. Biomass bunches were then skidded hot to the chipper.

While the whole tree and hybrid systems had been used previously on the Stanislaus National Forest, the cut-to-length system had not, and its feasibility in local terrain and stand conditions was unknown. The harvester's ability to delimb ponderosa pines in plantations, to fell relatively large and heavy trees in natural stands, and the forwarder's ability to traverse steep, broken slopes were of primary interest.

Stands

The systems were tested in two stand types, 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. Two replicate blocks were delineated in each stand type, and each block was divided into four units. One unit in each block was randomly assigned to each harvest system. The remaining units were designated as controls, to be harvested without the entry of tractive equipment.

The plantation pines were relatively open grown due to large initial spacing and precommercial thinning. Though the trees were mostly under 18" DBH, some limbs were over 4" in diameter, and the limbs commonly occurred in whorls of four or five. Large limbs were found almost down to the stump, although they were more brittle, slightly smaller and therefore easier to remove than limbs a few feet higher on the bole. The mixed conifers in the natural stands had smaller branches due to higher stand density and the range of species.

Skidding/forwarding distances ranged up to 1000 feet. Slopes in the plantation were 25 percent or less, and most skidding was favorable, i.e. loaded downhill. Unit boundaries in the mixed conifer blocks were placed to generally limit slopes to 35% or less. In some units, however, small areas of 40% slopes were included. Essentially all skidding and forwarding was planned to be on favorable grades.

Table 1. Stand characteristics.

	Plantation	Natural Stand
Species	Ponderosa pine	White fir, incense cedar, sugar pine, ponderosa pine
Average age (range), years	35	75 (40-100+)
Reserve stand prescription		enhance habitat for spotted owl
BA, ft2/acre	120	150
Trees/acre	75	120
Other reserve specs	all non-pine brush islands for habitat	all live trees > 18" DBH all snags > 16" DBH wildlife screens
Removals		
Merchantable		
MBF/acre	4.5	3
Trees/acre	75	45
Avg DBH, in	12	13
Biomass (excluding tops)		
Pieces/acre	3	95
Type	small trees	small live trees, dead, cull
Avg DBH	8	8

Harvesting operations were carried out from May 2 through June 7, 1994, so that comparisons of impacts to the soil could be carried out under conditions of near-maximum soil moisture, just after snow melt.

Data Collection

We collected time-motion data on all stump-to-truck activities. Productive cycle time elements and other variables associated with each activity are defined in Table 2. Delay times were also recorded and each was classified by activity and/or cause. For felling, harvesting and processing, we made an ocular estimate of the DBH of each tree, using scales on the head of the machine. Travel distances for felling and harvesting were also estimated by eye. Skidding and forwarding distances were estimated from distance tags that were prelocated in the stands. Slopes were measured with clinometers for within-stand activities. The numbers of trees in a sample of felled bunches were recorded, as were the diameter, length and type of each piece. These sampled bunches were numbered, and the numbers were recorded when they were skidded. For turns made up of unnumbered bunches, the numbers of pieces and type were recorded. Numbers of pieces were counted for the log 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. The time-motion cycle data was evaluated with regression analysis, ANOVA, t-tests and multiple range tests, using Statview 4.0. A few delays - time to exchange trucks, tie down bunks and chip slash - were calculated on a time per load basis. All other categories of productive delays were calculated as an additional percentage of productive cycle time and segregated by each system and stand type where appropriate.

Table 2. Definitions of time elements and associated variables for harvesting activities.

Timbco T420 Feller Buncher	
FBCycle, cmin	time per accumulation of trees in the head =FBMove*FBMoveFrac+FBFell
FBMove, cmin	time spent moving without any trees in the head
FBDistance, ft	straight line distance traveled during FBMove
Slope, %	fall line slope during FBMove
FBMoveFrac	fraction of cycles which include an FBMove
FBFell, cmin	time to fell all trees in the accumulation, including any time spent moving with trees in the head
DBH, in	DBH of each felled tree
Type	type of material for each piece: live, dead, dead and broken, cull
FBPiecesPerCycle	number of trees in the accumulation
Timbco T435/EP200 Harvester	
EPCycle, cmin	time per tree =EPMove*EPMoveFrac+EPFell+EPProcess
EPMove, cmin	time spent moving without a tree in the head
EPDist, ft	straight line distance traveled during EPMove
Slope, %	fall line slope during EPMove
EPMoveFrac	fraction of cycles which include an EPMove
EPFell, cmin	time to fell a tree until it hits the ground, including any time spent moving with the tree held vertical in the head
DBH, in	DBH of each felled tree
EPProcess, cmin	time to delimb and buck a tree, including time to place the top in a biomass pile
EPSawlogsPerTree	number of sawlogs cut from a tree
EPBiologsPerTree	number of biomass pieces cut from a tree
FMG1270 Harvester	
FMGCycle, cmin	time per tree =FMGMove*FMGMoveFrac+FMGFell+FMGProcess
FMGMove, cmin	time spent moving before felling
FMGDist, ft	straight line distance traveled during FMGMove
Slope, %	fall line slope during FMGMove
FMGMoveFrac	fraction of cycles which include an FMGMove
FMGFell, cmin	time to fell a tree until it hits the ground
DBH, in	DBH of each felled tree
FMGProcess, cmin	time to delimb and buck a tree
FMGSawlogsPerTree	number of sawlogs cut from a tree
FMGBiologsPerTree	number of biomass logs cut from a tree

Table 2. (continued)

<u>FMG1010 Forwarder</u>	
ForCycle, cmin	time per forwarder load =ForTravel+ForLoad+ForMoveWoods+ForUnload
ForTravel, cmin	sum of travel empty and travel loaded times
Distance, ft	one way slope distance from landing to center of area from which the load is accumulated
Slope, %	average fall line slope over Distance
ForLoad, cmin	sum of loading times per load
ForSawlogsPerLoad	number of sawlogs collected for the load
ForBiologsPerLoad	number of biomass logs collected for the load
ForLogsPerLoad	total number of logs per load
ForMoveWoods, cmin	sum of moving times while partially loaded
ForDistRange, ft	range of distance over which the load is accumulated, dmax-dmin
ForUnload, cmin	time to unload all logs at the landing
SawlogWeight, green lb	average per unit, estimated from log load data
BiologWeight, green lb	average per unit, estimated from chip van weights and piece counts
ForLoadWeight, green tons	SawlogWeight*ForSawlogsPerLoad+BiologWeight*ForBiologsPerLoad
<u>Grapple Skidders (Timberjack 450B and Caterpillar 528)</u>	
SkidCycle, cmin	time per turn =SkidTravelEmpty+SkidLoad+SkidMoveWoods+SkidTravelLoaded +SkidUnload
SkidTravelEmpty, cmin	time to travel from landing to first load point
Distance, ft	one way slope distance from landing to center of area from which turn is accumulated
Slope, %	average fall line slope over Distance
SkidLoad, cmin	sum of loading times per turn
SkidLogsPerTurn	total number of logs per turn
Type	type of turn: biomass or sawlog/merchantable
SkidMoveWoods, cmin	sum of moving times while partially loaded
SkidTravelLoaded, cmin	time to travel to landing with the complete turn
SkidUnload, cmin	time to unload at the landing
<u>Timberjack 90 Processor</u>	
ProcCycle, cmin	time per processor grapple load =Process+MoveTops*MoveTopsFrac
Process, cmin	time to delimb and buck a grapple load, including decking sawlogs
DBH, in	DBH of each processed tree
ProcSawlogsPerTree	number of sawlogs cut from a tree
ProcBiologsPerTree	number of biomass pieces cut from a tree
ProcStemsPerGrappleLoad	number of stems grappled
MoveTops, cmin	time to pile tops for chipping
MoveTopsFrac	fraction of cycles which include a MoveTops

Table 2. (continued)

Prentice 610 Loader	
LoadCycle, cmin	time to load a grapple load of logs
LogsPerSwing	number of logs in the grapple
LogVol, BF	average gross volume per log, =load volume/number of logs per load
BFPerSwing, BF	gross volume per swing, =Log Vol*LogsPerSwing
LoadExchangeTruck, cmin	time to put binders on a load, pull the loaded truck out, move in the empty truck and unload the trailer
TiedownFrontBunk, cmin	time to put binders on the first bunk of two, for the shortlog CTL loads
Morbark Chipper	
ChipCycle	time to chip a grapple load
ChipPiecesPerSwing	number of pieces in the grapple
BiologWeight, dry lb	average weight per piece, =2000*load weight, green tons*(1-average moisture content, wet basis)/number of pieces per load
ChipWtPerSwing, dry lb	weight per swing, =BiologWeight*ChipPiecesPerSwing
ChipSlashPerVan, cmin	time to chip limbs from WT processing, or other small slash
ChipExchangeTruck, cmin	time to pull the loaded van out and move in the empty van

Physical feasibility of the equipment was evaluated by recording subjective observations on performance, backed up by the time-motion results.

We tallied 100-percent of the removal trees. All sawlogs were scaled separately by unit, and weights and moisture content of biomass chip vans were recorded by unit. These data were used to calculate product recoveries for the three systems.

In most units, five circular fifth-acre plots were established in each study unit. A few units had ten tenth-acre plots and one small unit had three fifth-acre plots. Within each plot, trees were tallied as undamaged or damaged, and by diameter. Damaged trees were classified by type and extent of damage.

RESULTS AND DISCUSSION

Product Recovery and Characteristics

The tallies of removals have not yet been compiled, therefore no conclusions can yet be drawn about relative efficiency of total product recovery. As would be expected, however, there were marked differences between the CTL and other systems with respect to yield of biomass per unit of sawlogs, and average size of sawlogs (Table 3). For the CTL system, both average log size and biomass yield were approximately half of that for the other systems. These results reflected the shorter logs cut by the CTL harvester, and the removal in the woods of all limbs and tops from the biomass logs. Differences between stands were as expected. In the natural stand, the larger trees yielded larger logs on average, and the large numbers of small and dead trees resulted in higher ratios of biomass to sawlogs than in the plantation.

Table 3. Biomass/sawlog ratios and sawlog sizes.

	Whole Tree	Hybrid	Cut-To-Length
Ratio of Biomass to Sawlogs, BDT/gross MBF			
Plantation	2.21	1.89	0.98
Natural Stand	4.35	5.11	2.57
Average Sawlog Volume, gross BF			
Plantation	56.7	52.3	27.0
Natural Stand	65.8	63.0	30.4

Harvesting Productivity Relationships

Several indicator (one or zero) variables were used when evaluating the time study and related data. These variables are defined in Table 4.

Table 4. Indicator variables and definitions.

Variable	Definition
BiomassInd	for skidding: 1=biomass turn, 0=merchantable turn (merch whole tree or sawlog)
CTLInd	1=CTL system, 0=other system
CatInd	for skidding: 1=Caterpillar 528 and operator, 0=Timberjack 450B and operator
CullInd	1=cull log, 0=other material
DeadInd	1=dead tree (snag), 0=other material
ForOpInd	forwarder operator: 1=operator A, 0=operator B
HybridInd	1=hybrid system, 0=other system
PlantInd	1=plantation, 0=natural stand
TrailInd	for forwarder travel: 1=on main trail, 0=within stand

All the terms in the regression relationships reported below were highly significant ($p<.01$) unless noted. The same was true of the differences between means that are reported separately. The DelayFracs listed below for each machine are productive delays as additional fractions of productive cycle times.

A. Timbco T420 Feller Buncher

Since there were very few small trees in the plantation, the feller buncher did not accumulate more than one, in every case. In the natural stand, up to five of the smallest biomass trees could be accumulated. Accumulations on steeper slopes were slightly smaller, as they were if most of the trees in the accumulation were snags. Given the same diameter, accumulations for the hybrid system were slightly smaller than for the whole tree system.

As expected, move time was strongly affected by move distance but not by slope, as might be expected for the tracked carrier. For the same distance, times were longer for the hybrid system, possibly due to additional time to maneuver to the biomass trees which had to be selected from between the merchantable trees which were left standing for the harvester. On average, the feller buncher traveled less distance per move in the plantation than in the natural stand. This was probably due to the higher numbers of reserve trees per acre which had to be avoided in the natural stand. However, the feller buncher moved more frequently in the plantation, probably due to the very uniform spacing of the cut trees.

In the plantation, felling time was not related to tree diameter, probably because the diameter range was relatively small. For the natural stand, felling time increased with the number of pieces per accumulation and with tree diameter, and was slightly less for snags, possibly because they were closer to other trees. We should note that travel with one or more cut trees held in the head, up to distances of 50 feet or more, was common. The associated time was included in the FBFell element. While this movement slowed the feller bunchers, the creation of large bunches improved the productivity of the skidders.

FBPiecesPerCycle

for plantation =1

for natural stand =1.81-0.066*DBH+3.64/DBH-0.0058*Slope-0.27*HybridInd-0.10*DeadInd

R^2=0.23 n=3071

FBDistance, ft

for plantation=33.8 n=156

for natural stand=43.1 n=253

FBMove=19.2+0.77904*FBDistance+35.03*HybridInd

R2=.80 n=387

FBMoveFrac

for plantation=0.394

for natural stand=0.130

FBFell

for plantation=49.93 n=392

for natural stand=28.48+12.65*FBPieces+1.7498*DBH*FBPieces-3.94*DeadInd

R2=0.23 n=2745

FBCycle=FBMove*FBMoveFrac+FBFell

FBDelayFrac=0.0963

FBTimePerPiece=FBCycle*(1+FBDelayFrac)/FBPiecesPer Cycle

B. Timbco T435/EP200 Harvester

As expected, the number of sawlogs cut from a tree increased with diameter, but fewer logs were cut from the plantation trees due to their being shorter. One biomass top was cut from essentialy every tree, although two were taken from the occasional forked tree.

Move time increased with distance, but not with slope. Moves were slower in the natural stand, probably because of the higher density of the reserve stand and need to travel around the biomass bunches left by the feller buncher. Although there was no significant difference in travel differences between stands, the two means are reported separately because the travel conditions, i.e. densities of removals and reserves, were considered to be inherently different. This is borne out by the higher frequency of moves in the natural stand, which is probably related to the presence of the biomass piles, lower number of merchantable removals and higher number of reserve trees.

Both felling time and processing time increased with tree size. Felling time was slightly less in the plantation, possibly due to ease of identifying cut trees, but processing time was longer for all tree sizes and increased very rapidly with tree diameter, due to the large limbs on the bigger plantation trees. Like the feller bunchers, the EP200 harvester also traveled while carrying whole trees upright in its head to build larger bunches for the skidders. This travel time while holding a tree was include in the fell element.

There were more productive delays in the natural stand; most involved moving the bunches of biomass trees left by the feller buncher, or picking up and processing merchantable trees that had been felled by the feller buncher.

EPSawlogsPerTree=0.761+0.00317*DBH^2-0.00105*DBH^2*PlantInd

R2=0.18 n=1187

EPBiologsPerTree=1.01 n=1246

EPDist, ft

for plantation=44.0 n=191

for natural stand=47.4 n=107

EPMove=51.59+1.0115*EPDist+(-24.01-0.4937*EPDist)*PlantInd

R2=0.78 n=298

EPMoveFrac

for plantation=0.207

for natural stand=0.266

EPFell=39.82+0.11398*DBH^2-5.82*PlantInd

R2=0.08 n=1253

EPProcess=22.76+0.20025*DBH^2+(235.2-44.139*DBH+2.0265*DBH^2)*PlantInd

R2=0.26 n=1156

EPCycle=EPMove*EPMoveFrac+EPFell+EPProcess

EPDelayFrac
for plantation=0.024
for natural stand=0.182
EPTimePerTree=EPCycle*(1+EPDelayFrac)

C. FMG 1270 Harvester

As expected, more sawlogs were cut from the larger trees. Slightly fewer biomass logs were cut from the plantation trees as diameter increased.

Move time increased with both slope and distance as expected. As for the feller buncher, move distance was shorter in the plantation and moves occurred more frequently.

Felling time increased with diameter and slightly with slope. As for the EP200, processing time increased with diameter, and more drastically for the plantation trees. While processing times for the FMG were less than for the EP200, the percentage difference declined with tree size, indicating the FMG was approaching its design limit.

FMGSawlogsPerTree=-0.99+0.227*DBH
R2=0.46 n=1802
FMGBiologsPerTree=1.24+(0.33-0.056*DBH)*PlantInd
R2=0.07 n=1801
FMGDist
for plantation=13.5 n=205
for natural stand=17.0 n=203
FMGMove=24.09+1.126*FMGDist+0.04*FMGDist*Slope
R2=0.45 n=408
FMGMoveFrac
for plantation=0.255
for natural stand=0.207
FMGFell=13.1+1.149*DBH+0.329*Slope
R2=0.04 n=1725
FMGProcess=8.41+0.232*DBH^2+(64.27-14.994*DBH+0.818*DBH^2)*PlantInd
R2=0.43 n=1804
FMGCycle=FMGMove*FMGMoveFrac+FMGFell+FMGProcess
FMGDelayFrac=0.029
FMGTimePerTree=FMGCycle*(1+FMGDelayFrac)

D. FMG 1010 Forwarder

Although forwarding times were recorded on a single element basis, e.g. loading time per grapple swing, correlations between the sums of element times per load and the independent variables were higher than for the single element times. Therefore, the results for times per load are reported here.

In general, the forwarder followed the trail created by the harvester. Instead of turning around within the stand, the forwarder operator turned his seat around and backed the vehicle in empty, then loaded while traveling forward.
Because planners are likely to use the distance to the centroid of a harvest area as an input when estimating forwarding times, the distances used in our travel analysis were the averages of those for the logs picked up on each load. Use of this distance resulted in poor correlation between travel empty time and distance, and even lower correlation between travel loaded time and distance. In many cases, loads were collected over a large range of distance, so travel empty might be very long and travel empty very short. When the two times were summed, however, a very strong relationship with distance was apparent. As expected, time increased with distance and slope. (The slope term was significant, p=.044.) On a long

main trail leading from one of the natural stand units to the landing, travel was significantly faster. For all other units, the landings or decking areas were essentially at the edges of the units so, for those units, there was no travel on a main trail as defined here. Operator A traveled faster than operator B.

Loading and unloading times per load both increased with numbers of logs per load, and more for sawlogs than for biomass logs. (For unloading, the sawlogs term was significant, p=.027, the biomass logs term was not, p=.14.) The average unloading time for operator A was over a minute less than for operator B but not significantly (p=.082) because of the small sample size for operator A.

As would be expected, the total moving time between load elements was related to the distance range over which the load was assembled. If, for example, fewer trees per acre were removed or more sorts had to be made and each sort was forwarded separately, the distance range for each load would be larger and so would the move time.

ForLoadWeight, green tons=7.128+0.01054*LogWeight
R2=0.30 n=55
ForLogsPerLoad=122.44-0.1547*LogWeight
R2=0.63 n=55
ForDistRange=228 n=56
ForTravel=152.95+1.267*Distance+0.01224*Distance*Slope-0.4224*TrailInd*Distance-0.3474*ForOpInd*Distance
R2=0.58 n=71
Dist*Slope is signif (p=.044)
ForLoad=642.54+11.969*ForSawlogsPerLoad+10.669*ForBiologsPerLoad
R2=0.52 n=55
ForMoveWoods=458.91+0.808*ForDistRange
R2=0.21 n=55
ForUnload=498.63+6.689*ForSawlogsPerLoad+2.196*ForBiologsPerLoad-138.94*ForOpInd
R2=0.17 n=56
ForCycle=ForTravel+ForLoad+ForMoveWoods+ForUnload
ForDelayFrac=0.059
ForTimePerGT=ForCycle*(1+ForDelayFrac)/ForLoadWeight

E. Grapple Skidders (Timberjack 450B and Caterpillar 528)

The Timberjack skidder had a larger grapple than the Cat and therefore was able to carry more small biomass pieces per turn. (The Cat was not normally used to skid biomass bunches.) For sawlogs, there was no significant difference in pieces per load for the two machines, but larger numbers of hybrid sawlogs were carried than were whole trees, as would be expected.

Travel empty time increased with distance and with slope, which is logical as essentially all travel empty on slopes was uphill. Travel loaded time increased with distance but was not significantly affected by slope. The Cat was slower during both travel elements, but it was not possible to separate machine and operator effects because the skidder operators never switched machines during the study.

Loading times for biomass turns increased with the number of pieces per turn in the natural stands, but not in the plantation. (All plantation biomass observations were for the hybrid system.) For merchantable turns, loading time increased with both the number of pieces and slope. For both the biomass and merchantable turns, loading times were shorter in the plantation, probably due to the ease of access in the more open reserve stand.

The skidders combined more than one bunch to compose a full turn. Generally, the skidders needed to maneuver back and forth a few times to avoid reserve trees, sometimes rolling over the accumulated trees, to collect additional bunches. Compared to the forwarder with crane handling smaller logs, the grapple skidders had to maneuver a great deal more to pick up trees. Moving time between load elements increased with the number of pieces per turn, but less so for biomass because of the larger numbers of pieces per biomass bunch. Moving took longer for the hybrid system, because more bunches were accumulated to make the hybrid turns. For whole tree sawlog turns, over half consisted of a single bunch and therefore had zero moving time between load elements. Moves were shorter in the plantation, due again to the ease of maneuvering in the open stand.

Unloading times were over twice as long for hybrid sawlog turns as for others, due to the partial decking required. All other turns were dropped in front of either the whole tree processor or chipper.

Skidding biomass involved more productive delays than skidding sawlogs, especially to regrapple partial turns that had been accumulated and then dropped in the skid trail so the skidder could back up to get another bunch. And while moving slash from the landing back to the woods was a common delay in most situations, it was negligible when skidding hybrid sawlogs because almost no slash was being moved to the landing.

SkidLogsPerTurn
for biomass turns
for Timberjack=17.9 n=70
for Cat 528=12.1 n=28
for merchantable turns
for hybrid=6.39 n=85
for wholetree=4.75 n=106
SkidTravelEmpty=45.66+0.2217*Distance+0.004285*Slope*Distance+0.03971*CatInd*Distance
R2=0.58 n=283
SkidLoad
for biomass turns=80.59+4.33*(1-PlantInd)*SkidLogsPerTurn
R2=0.16 n=94
for merchantable turns=31.25+6.03*SkidLogsPerTurn+0.1777*Slope*SkidLogsPerTurn
-23.59*PlantInd
R2=0.20 n=179
SkidMoveWoods=6.36+14.692*SkidLogsPerTurn-6.298*BiomassInd*SkidLogsPerTurn
+54.78*HybridInd-83.08*PlantInd
R2=0.23 n=279
SkidTravelLoaded=40.82+0.2213*Distance+0.04956*CatInd*Distance
R2=0.58 n=283
SkidUnload
for merchantable hybrid turns=120.51 n=77
for all other turns=51.54 n=165
SkidCycle=SkidTravelEmpty+SkidLoad+SkidMoveWoods+SkidTravelLoaded+SkidUnload
SkidDelayFrac
for merchantable hybrid turns=0.154
for biomass turns=0.216
for all other turns=0.195
SkidTimePerLog=SkidCycle*(1+SkidDelayFrac)/SkidLogsPerTurn

F. Timberjack 90 Delimber/Processor

The processor only grappled one of the plantation trees at a time, because of the large limbs. Slightly more of the natural stand trees were processed per cycle, and the number was not significantly related to diameter. More sawlogs were cut from larger trees. Unlike the two harvesters, the processor cut fewer sawlogs from the natural stand trees than from the plantation trees. This may have been due to breakage of the longer trees during skidding.

Processing time increased with tree size, with the number of sawlogs cut from each tree and with the number of trees processed per cycle. Times were longer for plantation trees, due to limb size and the fact that limbs were present all the way from the butt to the top.

Time to pile tops for chipping was slightly less per occurrence in the plantation but tops were moved almost twice as frequently because of the large crowns.

ProcStemsPerGrappleLoad
for plantation=1 n=93
for natural stand=1.21 n=336
ProcSawlogsPerTree=0.871+0.00158*DBH^2+0.00075*DBH^2*PlantInd
R2=0.12 n=429
ProcBiologsPerTree=1.009 n=443
Process=-77.13+3.8*DBH+78.34*ProcSawlogsPerTree+27.54*ProcStemsPerGrappleLoad
+25.48*ProcSawlogsPerTree*PlantInd
R2=0.54 n=426
MoveTops
for plantation=53.22 n=49
for natural stand=66.82 n=100
MoveTopsFrac
for plantation=0.516
for natural stand=0.281
ProcCycle=Process+MoveTops*MoveTopsFrac
ProcDelayFrac=0.169
ProcTimePerTree=ProcCycle*(1+ProcDelayFrac)/ProcStemsPerGrappleLoad

G. Prentice 610 Loader

Loading time per swing increased with the number of logs per swing and with the average volume per swing. Time was slightly longer for the hybrid system, probably due to the hot loading situation versus loading out of neat cold decks built by either the whole tree processor or the CTL forwarder.

Placing binders on the first bunk of the CTL loads delayed loading by almost six minutes before the second bunk could be loaded.

BFPerSwing=-20.4+2.586*LogVol
R2=0.18 n=1224
LogsPerSwing=2.11 n=1224
LoadCycle=35.06+36.15*LogsPerSwing-3.109*LogsPerSwing^2+0.1482*BFPerSwing+12.81*HybridInd
R2=0.36 n=1224
LoadDelayFrac=0.098
LoadExchangeTruck=865. n=27
TiedownFrontBunk
for CTL loads only=591. n=4
LoadTimePerTruck=LoadTimePerSwing*1000*LoadVolume,MBF/BFPerSwing*(1+LoadDelayFrac)
+LoadExchangeTruck+TiedownFrontBunk
LoadTimePerMBF=LoadTimePerTruck/LoadVolume,MBF

Morbark 60/36 Chipper

Effective biomass piece weight was largest for the whole tree tops in the plantation, and next largest for the hybrid tops. Although no good reason for actual weight differences between these two is apparent, the large number of limbs chipped at the whole tree landings, left by the processor, increased the effective weight per whole tree piece because limbs were not included in the piece count. In the natural stand, weights per peice for the whole tree and hybrid systems were almost identical and not significantly different. For the CTL system, average piece weight was much smaller as expected due to the shorter lengths and removal of limbs. Only one van load of CTL material was observed being chipped in the natural stand, so no statistical conclusions can be drawn from the single observation of average piece weight. The one average was, however, calculated for a load produced from 280 pieces, so logic indicates that the true mean weight was probably less than for the other systems and more than for the plantation CTL pieces. Greater taper in the plantation trees would account for the difference between the two CTL weights.

Chipping time per swing increased with the number of pieces chipped and with average piece weight.

Time to chip slash was classified as a productive delay, but it contributed an average of almost half an hour per van for the loads coming from the whole tree system in the plantation. This contrasted with less than a minute per van for all other system/stand combinations.

BiologWeight, dry lb
    for plantation, whole tree=289 n=8
    for plantation, hybrid=193 n=9
    for natural stand, whole tree or hybrid=141 n=29
    for natural stand, CTL=98 n=1
    for plantation, CTL=80 n=4
ChipPiecesPerSwing=1.20+337.9/BiologWeight
    R2=0.13 n=2059
ChipWtPerSwing,DryLb=280+1.579*BiologWeight
    R2=0.09 n=2059
ChipCycle=24.96+2.463*ChipPiecesPerSwing+0.04982*BiologWeight
    R2=0.08 n=2059
ChipDelayFrac=.038
ChipSlashPerVan
    for plantation, whole tree=2786. n=7
    for all others=93. n=38
ChipExchangeTruck=529. n=22
ChipTimePerTruck=ChipTimePerSwing*2000*VanWeight,DryTons/ChipWtPerSwing
    *(1+ChipDelayFrac)+ChipSlashPerVan+ChipExchangeTruck
ChipTimePerDryTon=ChipTimePerTruck/VanWeight

I. Log Truck and Chip Van Loads

Log trucks were not weighed so it was not possible to determine if differences in load volumes were due to differences in weights or to differences in weight to volume ratio. Average volumes were higher in the natural stands for all three systems, so the differences between the two stand types were attributed to a difference in weight to volume ratio. CTL loads were smaller than those for the other systems, due mostly to the higher tare weight for the trailer used to haul the short logs. Hybrid loads were slightly larger than the whole tree loads, but this could have been due to random variation in load weight rather than inherent differences between the systems.

Average load volume, gross/net MBF

for plantation, whole tree	=3.10/3.02	n=13
for plantation, hybrid	=3.25/3.16	n=18
for plantation, CTL	=2.77/2.70	n=17
for natural stand, whole tree	=3.94/3.78	n=27
for natural stand, hybrid	=4.30/4.09	n=15
for natural stand, CTL	=3.34/3.19	n=6

Average chip van net weight n=85
=22.29 green tons
=12.79 BDT
Average chip moisture content, wet basis =42.6%

Harvesting Costs

The machine rate approach (Miyata 1980) was used to calculate hourly costs for each piece of equipment involved with the stump-to-truck activities (Table 5). Key assumptions included current replacement costs for equipment, 20% salvage value, life of five years, 2000 scheduled hours per year, and maximum utilization rates of 65%. For equipment no longer manufactured, purchase prices of current similar models were used. Maintenance and repair percentages and S&E costs were taken from Brinker et al (1989), and the S&E costs were adjusted for inflation. A labor rate of $15 per hour was assumed, plus 50% loading. For trucking, a flat rate of $50 per scheduled hour was assumed, and utilization was set at 90%.

Table 5. Machine replacement prices and hourly costs.

Machine	Purchase Price, $	Hourly Cost, $/SH
Timbco T420 feller buncher with 20" shear	240,000	67
Timbco T435 with Equipment Repair EP200 harvester head	370,000	93
Timberjack 450B skidder	160,000	55
Timberjack 90 processor	270,000	75
FMG Timberjack 1270 with 762B harvester head	460,000	120
FMG Timberjack 1010 forwarder	290,000	83
Prentice 610 loader	340,000	89
Prentice 325 loader	200,000	59
Morbark 60/36 chipper	260,000	86
Log truck/trailer or chip truck/van		50

To compare the economics of the three systems, a standard set of conditions was set for each stand. 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%. Production rates at maximum utilization were calculated from the regression relationships, for the biomass component and sawlog component. It was assumed that the Timberjack skidder would carry out all the skidding. Forwarding productivity was based on the average of the two operators. The activities allocated to the biomass were incremental as much as possible, i.e. all felling of non-merchantable trees, skidding of biomass bunches, forwarding of biomass logs and all chipping. Some of the biomass costs were not easy to break out and were therefore assigned to the sawlogs. These included handling of the tops of merchantable trees by the harvesters, skidding of the tops on merchantable trees for the whole tree system, and decking of tops by the whole tree processor.

For hot activities, e.g. skidding and chipping in the whole tree and hybrid systems, the numbers of machines were balanced to give minimum costs, although processing, loading and chipping were lomited to a single machine per system. For the cut-to-length system, harvesting and forwarding were balanced for the sum of biomass and sawlogs rather than for each separately. Because the logger has several feller bunchers which he operates independently of other equipment, felling in the whole tree and hybrid systems was not balanced to the other activities.

Observed average times for truck travel for a 40 mile one-way haul and unloading were combined with predicted loading times to give productive time per load. Observed averages were used for truck load volumes and dry weight of chips per van. Hourly costs and production rates were combined to give total dollars per acre for each activity and product. The total dollars for sawlogs and for biomass were divided by the total amount of the respective product to give costs per gross MBF for the sawlogs and costs per ton for the biomass, for the plantation (Table 6) and natural stand (Table 7).

Table 6. Costs per unit of product for the three systems in the plantation.

Whole Tree		Hybrid		Cut To Length	
Sawlogs (costs in $/gross MBF)					
Fell&Bunch	22	Harvest	46	Harvest	47
Skid	43	Skid	26	Forward	54
Process	58				
Load	34	Load	33	Load	53
Haul	55	Haul	53	Haul	67
Stump-Mill	213	Stump-Mill	158	Stump-Mill	222
Biomass (costs in $/BDT)					
Fell&Bunch	0.3	Harvest	0.5	Harvest	2.0
Skid	5.8	Skid	5.9	Forward	22.2
				Reskid	4.0
Chip	8.8	Chip	4.5	Chip	6.0
Haul	15.2	Haul	13.4	Haul	14.0
Stump-Mill	30.1	Stump-Mill	24.3	Stump-Mill	48.2

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

Table 7. Costs per unit of product for the three systems in the plantation natural stand.

Whole Tree		Hybrid		Cut To Length	
Sawlogs (costs in $/gross MBF)					
Fell&Bunch	20	Harvest	64	Harvest	58
Skid	28	Skid	35	Forward	44
Process	38				
Load	30	Load	35	Load	53
Haul	44	Haul	44	Haul	60
Stump-Mill	160	Stump-Mill	178	Stump-Mill	214
Biomass (costs in $/BDT)					
Fell&Bunch	8.5	Fell&Bunch	9.7	Harvest	26.1
Skid	6.5	Skid	10.2	Forward	17.0
				Reskid	3.7
Chip	5.0	Chip	5.2	Chip	5.6
Haul	13.6	Haul	13.6	Haul	13.8
Stump-Mill	33.5	Stump-Mill	38.8	Stump-Mill	66.2

The whole tree system was the 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. The hybrid system was more expensive in the natural stand, due to increased moving times for both the harvester and the skidder. As in the plantation, the cut-to-length system was costlier than either the whole tree or hybrid methods.

Values of logs and chips, delivered to the mill or plant, are listed in Table 8. Sawlog values were based on estimates from the mill after their experience with handling the material produced during the study (Durrell, personal communication 1994). Values for the natural stand thinnings were $300 to $325 per MBF for pine and white fir, and $200 to $225 per MBF for incense cedar. The worth of the plantation pine thinnings, $200 to $225 per MBF, was less than the natural stand pine because of the lower average log size and higher lumber manufacturing costs. We used the delivered value for chips paid by the powerplant, although the price has subsequently dropped because of changes in the biomass power industry in California.

Table 8. Product values, delivered to the mill/plant.

	Plantation	Natural Stand
Average log value, $/net MBF	200-225	300
Net MBF/gross MBF	0.97	0.95
Density, green lb/gross BF	15	13
Chip value, $/BDT	40	40
Moisture content, %, wet basis	43	43

The values, costs and product yield were combined to give a net return for each product, and per acre (Table 9). It should be noted that some costs associated with harvesting, e.g. supervision, road construction and maintenance, slash treatment, and margin for profit and risk, must be deducted from these reported net values to give a more accurate picture of the return to the landowner.

Table 9. Net values of products for the three systems in the two stand types.

	Whole Tree	Hybrid	Cut-To-Length
Plantation			
Sawlog value, $/net MBF	-7.	47.	-16.
Biomass value, $/BDT	9.9	15.7	-8.2
Sawlog value, $/acre	-31.	213.	-72.
Biomass value, $/acre	112.	119.	-23.
Total value, $/acre	81.	332.	-95.
Natural Stand			
Sawlog value, $/net MBF	125.	107.	71.
Biomass value, $/BDT	6.5	1.2	-26.2
Sawlog value, $/acre	367.	314.	207.
Biomass value, $/acre	64.	12.	-223.
Total value, $/acre	431.	326.	-16.

Harvesting costs might be reduced in several ways. The loader was oversized for the material; a well-matched machine is expected to reduce loading costs by a third. Chipping costs for the whole tree system in the plantation could be reduced by having the skidders distribute limbs from processing back in the woods. Harvesters and processors with higher delimbing forces could reduce the times to delimb the larger plantation trees. A larger forwarder would reduce travel distance per unit of material and travel faster on the broken terrain. The assumption that the harvester and forwarder must have equal scheduled hours may be too conservative. Since they do not work hot, the least productive of the two could work longer hours, within reasonable limits. A lighter short log trailer would reduce hauling costs for the cut-to-length logs, and use of setout trailers would eliminate the loader cost at some additional forwarding cost if the forwarder was more limiting than the harvester. We have not yet used the relationships to investigate how the systems compare over the range of skid distance, slope, or average tree size.

Physical Limitations

A. Whole Tree System

The feller bunchers and the skidders were able to negotiate the terrain on all the study units.

Bole diameter and tree weight was not generally a limitation for the feller buncher. However, it had difficulty with one 20" DBH (measured) tree in the natural stand. Unable to sever the tree at the stump, the operator cut the tree at ten feet above the ground, then made two cuts to fell the butt log.

Although the results showed the stroke delimber to be comparatively slow in the plantation, it removed all limbs without obvious delays or difficulty and with essentially no damage to the boles.

B. Cut-To-Length System

Terrain was not too steep or broken for forwarding on any of the cut-to-length units, but slope did influence the forwarding pattern. Forwarder trails were generally directly downhill on slopes over 10%. On part of one unit, however, sidelopes led to an unusual forwarding pattern. This part of the unit was 560 feet north-south by 280 feet east-west, sloping 15% down to the west. Rather than a few long north-south trails, the operators laid out several trails heading downhill to the west, with a main trail on a flatter bench at the west edge of the unit. The advantage of downhill forwarding was considered to offset the longer travel distances.

While most forwarder trails had cross slopes of 15% or less, a main trail had a cross slope of 23% at one point. The forwarder operator usually held one grapple load of logs out to the uphill side of the forwarder as a counterweight when crossing this point. He also traveled at a much reduced speed at that point.

In the natural stand, one strip cut by the harvester traversed a steep slope with a short 42% grade and rocky ground. In order to avoid forwarding on the steepest slope, the operator forwarded some material uphill and across to an adjacent forwarder trail. To demonstrate the forwarder's capability, some loads were hauled down the 42% grade.

Although the forwarder did not generally travel uphill on steep slopes while fully loaded, it was observed forwarding fully loaded up a 23% grade and half loaded on a 35% slope, at reduced speed.

No trees designated for harvest in the cut-to-length units were too large for the harvester in terms of weight or bole diameter. The maximum cut tree butt diameter observed was 25" on a snag in the natural stand. This had to be felled by cutting from both sides. The largest trees were snags, which were lighter than comparable sixed green trees would have been. The largest green trees harvested were approximately 18" DBH.

The harvester head was successful in removing limbs 2.0 inches or less in diameter. The harvester attempted to process numerous trees with limbs up to 2.2 or 2.3 inches in diameter, but this generally required many runs or strokes of the head to sever the limbs. On the plantation units, a total of less than ten designated cut trees were either partially delimbed and then abandoned or left standing, due to limb size. These trees had limbs of 2.5 inches or more in diameter. Running the tree into the delimbing knives more than several times was time consuming and seemed, subjectively, to be rough on the equipment. The harvester operator said that in a large scale operation a faller using a chainsaw should fell and delimb the trees with oversize limbs, working ahead of the harvester.

C. Hybrid System

As with the whole tree system, the feller buncher, harvester and skidders were able to negotiate the terrain on all units.

As with the other systems, bole diameters and tree weights did not pose a problem for the hybrid system. The EP 200 head is capable cutting trees up to 24" at the butt.

By chance, the largest limbs found on the study were in one of the hybrid units in the plantation. With its heavy duty feed rolls and aggressive 3/4" teeth, the EP 200 head was able to remove limbs up to 4.4" in diameter. The feed roll teeth generally made impressions into the bole wood even when the limbs were small and easily removed. Removing the largest limbs, however, required many runs through the head. The feed rolls had ample torque, except on the limbiest trees when one roll sheared off the bark and began to slip. Because the hydraulic motors powering the rolls were plumbed in parallel, hydraulic pressure to all motors dropped when one roll slipped, causing the others to stall. The slipping roll tended to shred the outer bole and possibly reduce usable bole volume. As with the cut-to-length system, it appeared that delimbing excessively large-limbed trees might be too hard on the machine for everyday operations. Some of the largest trees were left only partially delimbed, and the multiple stroking caused measurement errors which the operator remedied by dropping the tree and regrappling it at the base. During the study the delimbing knives were sharpened, resulting in a marked improvement in delimbing performance. By that time, however, the trees with the largest limbs had already been harvested.

Damage to Residual Trees

Damage levels were low in the plantations, averaging 3 to 4% for each of the three harvest methods, and there were no significant differences between methods. Most damage was in small scars. In the natural stands, damage levels averaged 13%, 15% and 10% for the WT, hybrid and CTL methods, respectively. Most of the damaged trees were small and suppressed.

Soil Disturbance

No quantitative analysis of soil impacts is yet available. Observations, however, visually indicated differences in machine operation and disturbance.

For the CTL system, harvester and forwarder trails were spaced at approximately 50 feet. Areas between trails were not traversed by the equipment. The harvester was able to place limbs and tops either in its trail or alongside. In the study stands it was considered more useful to place slash on the trail. This slash was compressed by the tires, reducing fire hazard, and distributed the weight of the tire loads, reducing soil compaction. In areas where few trees had been harvested, there was little slash on the trail . Some bare soil and limited rutting were observed in these cases. Over most of the harvest area, however, slash covered the forwarder trails and no apparent rutting was observed. The greatest soil disturbance observed on the cut-to-length units was caused by tire slip on rocky trails of 35%+ slope in the natural stand.

On gentle slopes, the whole tree and hybrid systems created more disturbance than did the CTL system, but most was confined to the main trails. Additional soil displacement occurred, however, on steeper slopes where the tracks and tires slipped more. The frequent travel motion of the feller bunchers and harvester to create larger bunches for skidding increased the soil impacts of those machines. Especially in the natural stand, the limited reach of the skidders resulted in considerable maneuvering to pick up trees. Turning the skidder around was especially apt to displace duff and soil. While the main skid trails were confined to pre-flagged locations, generally pre-existing skid trails, the skidders covered most of the harvest area with one or two pass trails.

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