Tech Notes

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Economics and Environmental Effects of Fuel Reduction at Limber Jim

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ABSTRACT

Fuel reduction by mechanical thinning and removal was studied in mixed-conifer stands on Limber Jim ridge, La Grande District, Wallowa-Whitman National Forest, between 1995 and 1997. Mixed-conifer stands on this ridge had some of the highest fuel loads on La Grande District, up to 80 tons per acre. A single-grip harvester was coupled with either a skyline yarder or a forwarder, and fuel reduction, soil disturbance, and operational economics were measured in three replicate stands. The two retrieval systems achieved nearly identical patterns of fuel and standing stem reduction, with 53% of fuel and 36% of stems left after harvest in all units. In forwarder units more total material was removed per acre compared to skyline units (57.1 tons v. 48.1 tons), though this difference was not statistically significant. About 80% of the total material removed was dead. The only difference in pattern of fuel reduction was for the 9.1-20 in. size class, where skyline retrieval left 45% of pre-treatment fuel, compared to 74% for the forwarder. Soil disturbance was statistically identical for the two retrieval systems, with 6.0% area disturbed for the forwarder, and 7.3% for the skyline yarder; both retrieval methods were well within the 15% Region 6 standard, assuming 5% disturbance for existing roads. However, the pattern of soil disturbance was different for the two systems, with the forwarder causing signficantly more compaction than the skyline yarder (1.7% v. 0.2%; P=0.03); there was a trend toward less displacement with the use of the forwarder (4.3% v. 7.0%; P=0.13). Overall, the entire project was a narrow economic success, at just over $10/ton profit. Revenue in skyline units was slightly higher than forwarder units ($63/ton v. $61/ton); this difference was due to the slightly greater harvest of sawlog material in the skyline units. However, operational cost was $71/ton in the skyline units, and $42/ton in the fowarder units. This difference resulted in a net revenue loss of $10/ton in the skyline units, and in a net revenue gain of $19/ton in the forwarder units. Relatively flat ground and small-diameter/low-value material clearly favored the fowarding machine at Limber Jim; a larger average stem size and greater slope deflection would likely favor the skyline system. These results are discussed in the context of adaptive management, in which operational experiments provide information that allows the manager to assess economic/environmental tradeoffs inherent in management decisions.

INTRODUCTION

The forests of the Blue Mountains have evolved in the context of a disturbance regime dominated by fire (Agee 1996). Fire suppression over the past 80 years has led to significant accumulation of fuel, increasing the probability of catastrophic wildfire over much of the Blue Mountain landscape (Gast et al. 1991, Agee 1996). On federal lands, the reduction of fuel has become a priority objective, especially in those stands that are considered to be furthest from historical conditions (primarily dry forest types), or those that present dangers to human settlements (Quigley and Cole 1997). The scale of the fuel problem is so large that the only practical methods for fuel reduction are landscape prescribed fire, and thinning/removal by mechanized harvest systems. A recent survey suggests that the majority of citizens of the Blue Mountains strongly support either method of fuel reduction on federal lands, but have a slight preference for mechanical thinning/removal on some sites, primarily because of the potential for economic gain (Shindler 1997). Mechanical thinning/removal is also preferred by managers in more mesic systems typical of higher elevations, that have historically experienced stand replacement fires as the primary disturbance agent.

Although much is known about the operational feasibility of mechanized harvest systems in general (Kellogg et al. 1992), there is very little information on how different systems compare with respect to fuel reduction objectives, economics, and environmental effects. If managers are to effectively deal with fuel accumulations by mechanical thinning, they need information on the operational economics and environmental effects of available systems in the context of fuel reduction. This paper compares two such mechanized systems for the Limber Jim fuel reduction project on the La Grande Ranger District (Wallowa-Whitman National Forest): a single-grip harvester for felling, coupled with either a forwarder or a skyline system for retrieval of logs to the landing. By simultaneously measuring fuel reduction, economics, and environmental effects, this "management experiment" is intended to provide managers with better information on the tradeoffs inherent in the choice of these harvest systems.

Management Objectives and Prescription

The Limber Jim Fuel Reduction Project was designed to reduce fuel within a corridor on the ridge between Limber Jim and Hoodoo Creeks on the west and the La Grande municipal watershed (Beaver Creek) on the east. The project was classified as high priority by the La Grande District primarily because of the heavy accumulations of fuel on the ridge and in the watershed that serves as "backup" water supply for La Grande. Fuel reduction activity occurred within 1000 feet of either side of USFS road 5140, between the headwaters of Hoodoo Creek (accessed by the 5140-400 road) on the north and the headwaters of Muir Creek on the south. At the time of harvest, the Limber Jim project area contained a diverse array of mixed-conifer stands typical of higher elevations, some dominated by lodgepole pine, others by subalpine fir, or western larch. Primary tree species in order of abundance at Limber Jim were lodgepole pine, subalpine fir, western larch, grand fir, Douglas-fir, Engelmann spruce, and ponderosa pine. Many of the more dominant lodgepole pine stands were harvested in the 1980s using regeneration systems. The interspersed mixed-conifer stands had not been entered prior to the study.

The overall goal of the project was to reduce fuel on Limber Jim ridge and protect the municipal watershed from wildfires starting in the Upper Grande Ronde drainage, an area of frequent lightning strikes.

Within this goal, the three management objectives were to:

1) Reduce crown fire potential.
2) Meet Region 6 soil productivity protection standards.
3) Pay for management with sale of harvested product.

Although detailed prescriptions varied somewhat based on individual stand conditions, the overall objective was to reduce the amount of standing and down material between 4 in. and 15 in. large-end diameter. The prescription specified removal of all material at least 8 ft. long and having a small-end diameter >1 in., with the constraint that at least 40 pieces of down wood be left evenly distributed per acre, having a minimum 6 in. large-end diameter and 30 ft. length. Green trees with greater than 30% crown were left (except where they interfered with harvest activities), as well as standing and down dead wood >15 in. diameter. The expectation was that most of the fuel reduction would occur in the intermediate fuel size (3-15 in. diameter), with larger material left as per the prescription, and fine fuel (< 3 in. diameter) increasing because of logging activity.

Research Objectives

Research at Limber Jim was designed and carried out as a "management experiment," in which experimental treatments were incorporated into a management scheme with the objective of fuel reduction. Research was both multidisciplinary in that both ecological and economic aspects of the fuel issue were addressed, and integrated, in that data collected within each discipline were analyzed within the context of the entire data set. The result is information that will allow the manager to assess economic and environmental tradeoffs associated with the choice of a particular fuel reduction tool.

Overall, research at Limber Jim consisted of an "operations" experiment, to compare efficiency of different log retrieval systems used for fuel reduction, and a "pine marten" experiment, to compare habitat effects of different fuel reduction prescriptions. Pine marten results will be reported in a PNW Station *Science Findings* publication, and in an additional scientific publication written by Evelyn Bull (La Grande Lab, PNW Station). Although the core operations research is reported here, several additional analyses will be reported at a later date, including silviculture and residual stand effects (Andrew Youngblood), wildlife log analysis (Torolf Torgersen), soil biota effects (Chris Niwa), stand visualization (Robert McGaughey), and more detailed analyses of the harvest operations (Erik Drews, Bruce Hartsough, James Doyal, Loren Kellogg).

The operations research compared forwarding and skyline yarding, each working with the same single-grip harvester. Work discussed in this paper followed three research objectives:

1) Measure fuel before and after harvest.
2) Measure impacts of harvest on soils.
3) Measure production rates, harvest costs, and revenues.

METHODS & RESULTS

Overall Experimental Design

Seven distinct research units were chosen from 18 units in which management occurred at Limber Jim (Figure 1). Research units varied in size from 6.5 to 23 acres, and from nearly flat to about 20% slope. The Limber Jim area contained some of the highest fuel loads on the La Grande Ranger District, with many stands exhibiting fuel model 10 conditions, in which there is a high potential for crowning, spotting, and torching within a wildfire situation. Six of the units consisted of pairs, in which one unit of the pair was randomly chosen to be a forwarder unit, and the other unit of the pair was assigned to be a skyline unit. This design had two purposes: 1) to replicate the comparison between the forwarder and the skyline systems three times, the minimum sample size needed for calculation of mean and variance; and 2) to provide the fairest possible comparison between the two retrieval systems. Replication was essential to determine if differences between the two systems were real, or merely dependent on peculiar stand conditions. Logs in the seventh unit were retrieved with a skidder, and results on economics and soils of this unreplicated case study are compared descriptively to the results from the paired units.

Objective 1: Fuel and Stem Reduction

Methods—Fuel is defined as down and dead woody material of all sizes (0-3 in. diameter, 3-9 in., 9-20 in., and >20 in.), plus the forest floor (litter and duff). Stems are live standing material. Fuel and stems were measured in all experimental units before (July to September 1995) and after (July to September 1997) harvest. Because no untreated control units were established, it was assumed that natural changes in fuel and stem levels between 1995 and 1997 were the same in all experimental units.

A minimum of 18 plots were systematically located in each unit in 1995, on a transect defined by the unit's particular size and shape. Plot centers were located at least 66 ft. apart and at least 100 ft. from fire lines, roads, campgrounds, or other human disturbance features. Plot centers were permanently located in 1995 with rebar pushed below the surface, and were then flagged and mapped so that they could be relocated in 1997.

Down woody fuel was measured on three 66 ft. lines per plot using the planar intercept method (Brown 1974). The bearing of the first line was determined randomly; the second and third lines were located 120 and 240 degrees in a clockwise direction from the first line. Diameter, species, and decay class for each intersected 1000-hr fuel (>3.1 in. diameter) were recorded along each transect line. 100-hr fuel (1.1-3 in. diameter) was counted along each transect line, while 10-hr fuel (0.26-1 in. diameter) was counted along the first 6.6 ft. of each line. One-hr fuel (<0.25 in.) was estimated from 10-hr counts. Depth of pre-treatment litter and duff was measured at three points (20, 40, and 60 ft.) to the right of each transect line; post-treatment litter and duff were measured to the left of each transect line at the same three points.

Standing stems were measured with a combined fixed-plot/variable plot method, using one of the three transects at each down wood plot center. Fuel and stem data were collected by La Grande District fire personnel; fuel data were entered and analyzed by the Seattle Lab of the PNW Station (Roger Ottmar), while stem data were entered and analyzed by the La Grande District (Annette Pepin, Tom Burry).

Results—Overall at Limber Jim, fuel was reduced to 53% of pre-treatment, from an average of 55.6 tons to an average of 29.4 tons post-treatment (Figure 2). Fuel was reduced in all fuel classes except the 0.0-3.0 in. diameter, where tonnage increased by an average of 11%. Fuel reduction was greatest in the 3.1-6.0 in.

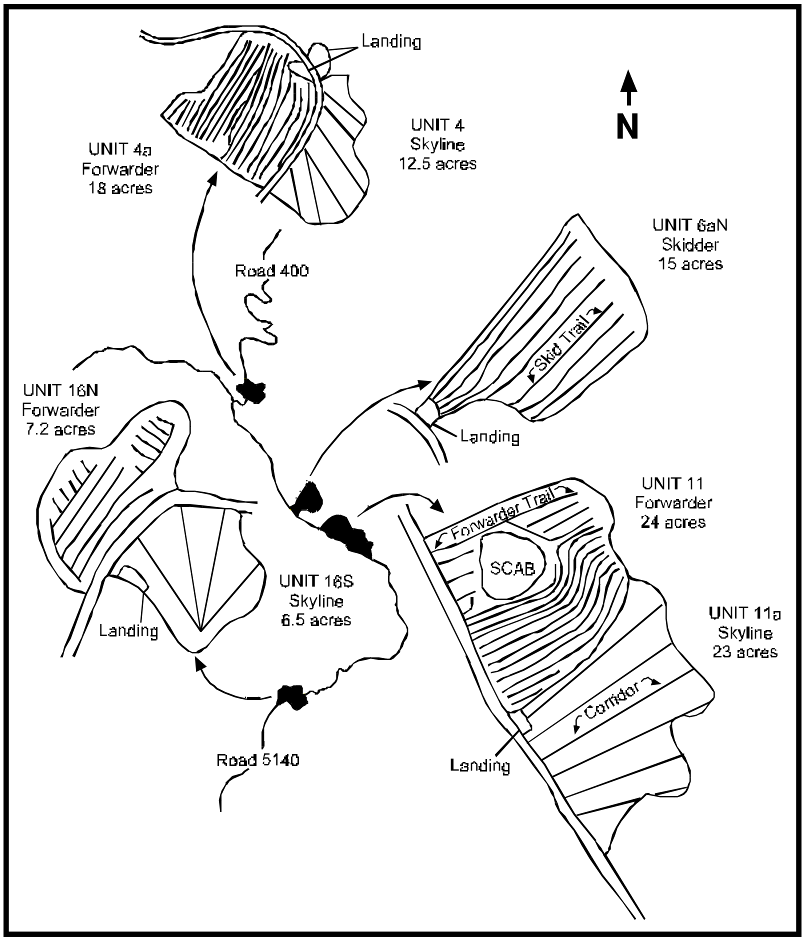

Figure 1— Layout of experimental units at Limber Jim. Map shows Road 5140 and its spur, Road 400, with the seven experimental units located and drawn to scale (solid black). Each unit is then blown up to show location of landings, trails, corridors, and other primary features.

size class (47% of pre-treatment), and the 6.1-9.0 in. size class (29% of pre-treatment). While litter was reduced only slightly, post-treatment duff was 42% of pre-treatment. Forest floor depth (litter + duff) declined from an average of 1.8 in. to 1.0 in. (56% of pre-treatment), and fuel height declined from an average of 6.0 in. to 4.6 in. (77% of pre-treatment). It is important to note that since harvesting would not be expected to consume duff, observed declines probably reflect *redistribution* of duff. The percentage of sound logs (logs that retain cylindrical form after lifting) declined from 74% to 69% after treatment.

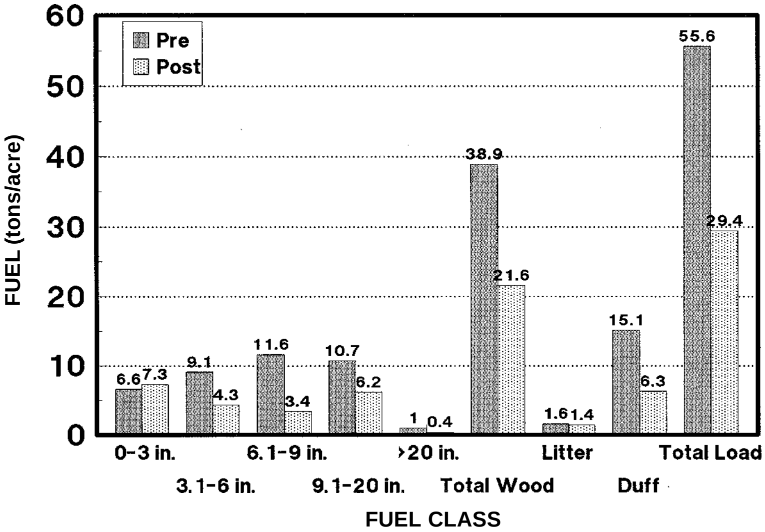

Figure 2— Fuel (tons/acre) for all Limber Jim units, PRE (1995) and POST (1997) treatment.

When the ground-based and skyline systems are compared, it is clear that for the most part, the systems achieved statistically equivalent patterns of fuel reduction (Figure 3). Fine fuels increased slightly with both methods, while intermediate size classes (3.1-9.0 in.) and duff decreased to an average of 43% of pre-treatment levels. Skyline retrieval left more litter than ground-based retrieval, although this difference was not significant. The only statistically significant difference in fuel reduction between the two methods was for the 9.1-20.0 in. size class, where skyline retrieval left 45% of pre-treatment fuel, compared to 74% for ground-based retrieval. This fuel size class combines fuel that was to be removed (9.1-15 in.) and fuel that was to be left (15.1-20 in.), and so it is unclear whether the observed difference was due to variation between the units themselves, or to variation in the removals. From the observed consistency of harvester operation, and from comparable results in the other size classes, the difference in the 9.1-20 in. size class is most likely due to variation in the material distribution between the units, and not due to any functional difference in how the retrieval systems performed.

Stem densities were reduced to an average 36% of initial conditions (Figure 4). The most significant reductions occurred in the 1.0-3.9 in. and 4.0-7.9 in. size classes, in which 28% and 13% of stems were left standing respectively. As per prescription, stem densities in the >15.0 in. DBH size class were left unchanged. The skyline and forwarder systems performed identically with respect to standing material, in every stem size class (Figure 5). There was a slight increase in the >15 in. component in the skyline units (to 111%), which can be attributed either to sampling error, tree fall, or both.

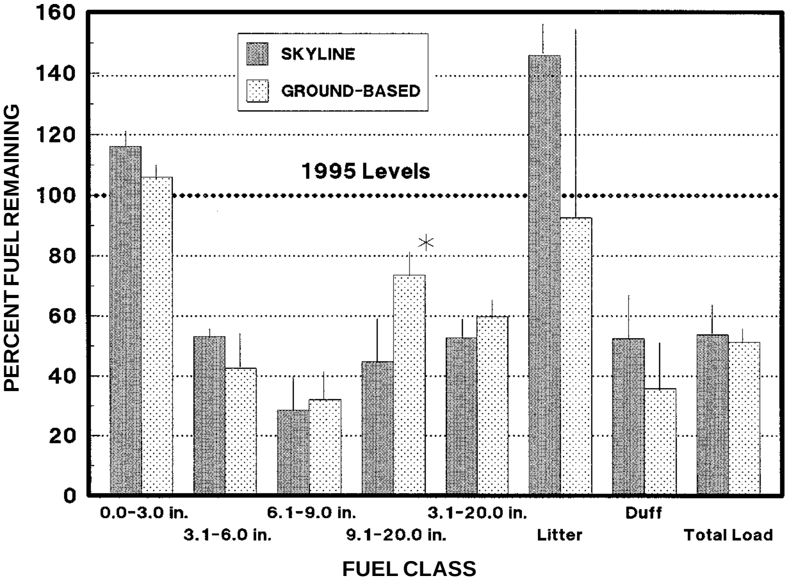

Figure 3— Percent fuel remaining +/- 95% confidence limits for skyline and ground-based units at Limber Jim (denotes significant difference between skyline and ground-based systems for indicated class).*

Objective 2: Soil Disturbance and Hydrology

Methods—Soil effects were measured only within treated units at Limber Jim; the existing permanent road system (road 5140 and the 400 spur road) was not included as part of the affected area. Hence because roads are assumed to occupy 5% of the project area, the Region 6 allowable soil impact on an area basis was 15% for the study area (USDA 1996).

Following harvest (from July to October 1997), soil effects were estimated using a stratified sampling design. Each of the seven treated units (3 forwarder, 3 skyline, 1 skidder) was divided into three strata: landing, corridor, and intercorridor. Within each unit, we took from 4 to 7 subsamples in landings, from 30 to 40 subsamples in corridors/skid trails, and from 15 to 20 subsamples between corridors (intercorridors).

A soil disturbance subsample consisted of an assessment of detrimental soil impact in two categories: displacement and compaction. Displacement is the removal and transport of

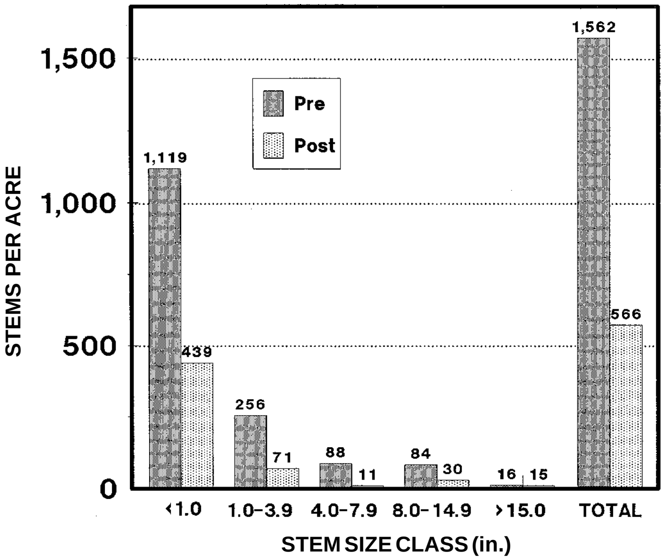

Figure 4 — Mean stems per acre for all Limber Jim units, PRE (1995) and POST (1997) treatment.

soils by mechanical forces. Since it is a surface phenomenon, displacement was judged visually. Compaction is associated with an increase in bulk density, a reduction in macropore space, and/or an increase in soil strength, and is caused by application of weight and vibration. Compaction is a subsurface phenomenon, and was estimated by measuring bulk density with a nuclear densimeter. It is recogized that macropore space or soil strength may be more reliable measures of compaction (Robert Powers, PSW Station, personal communication), but since the Region 6 standard is based on bulk density, we chose to measure this variable.

A subsample consisted of the following information: 1) visual assessment of soil displacement, in which greater than 100 ft^2 of displaced soil in an area at least 5ft. wide and within a 5ft. radius of the sample point was considered detrimentally affected; 2) assessment of soil bulk density using the nuclear densimeter. For this assessment, two samples of bulk density taken at right angles to each other were averaged (to account for local variation owing to roots or rocks) to create one subsample value, which was then compared to the average undisturbed bulk density for that treated unit. Undisturbed bulk densities were taken in areas between harvester trails that had no evident disturbance. If bulk density of the disturbed subsample was greater than 120% of the average undisturbed value (Region 6 standard for ash soils), the subsample was recorded as detrimentally compacted. Bulk density was also estimated by taking core samples at several of the locations in which the nuclear densimeter was used. The correlation of estimates taken by core and by densimeter was then used to determine how well the nuclear densimeter estimated bulk density compared to the more traditional core samples.

Subsample locations within landings were selected randomly. Subsamples within corridors were taken at regular distances from landings to average out the expected effect of attenuated disturbance with greater distance from landings. Similarly, because forwarder trails are characterized by two tracks separated by a relatively unimpacted central ridge, forwarder corridors were divided into two substrata: the tire track and the central area between the tire tracks. Finally, intercorridor subsamples were located by using randomly selected coordinates from every other corridor subsample taken, in forwarder, skidder, and skyline units. Percent area affected was then estimated by multiplying the percent of each stratum affected by the percentage area occupied by that stratum. All soils data were collected and analyzed by personnel from Oregon State University (Mark Taratoot).

Results—Estimates of soil bulk density made by the nuclear densimeter were significantly correlated (P=0.005) with estimates from soil cores (Figure 6). About 50% of the variance in the relation between nuclear densimeter and soil core samples is explained by the single regression line, and the slope of 0.86 indicates that the two methods measure bulk density comparably, with the nuclear densimeter giving slightly higher values in each pair of samples. Thus the nuclear densimeter performed adequately for estimating bulk density under the observed conditions. However, given the amount of unexplained variance (50%) for estimation of bulk density, in future the densimeter should be tested against core sampling on a unit by unit basis, to insure the reliability of the information.

Of the 106 total acres assessed in the experiment, 8.8 acres (8%) meet the Region 6 definition of detrimental compaction and displacement. Displacement was the most common type of soil disturbance, with 6.8 acres displaced

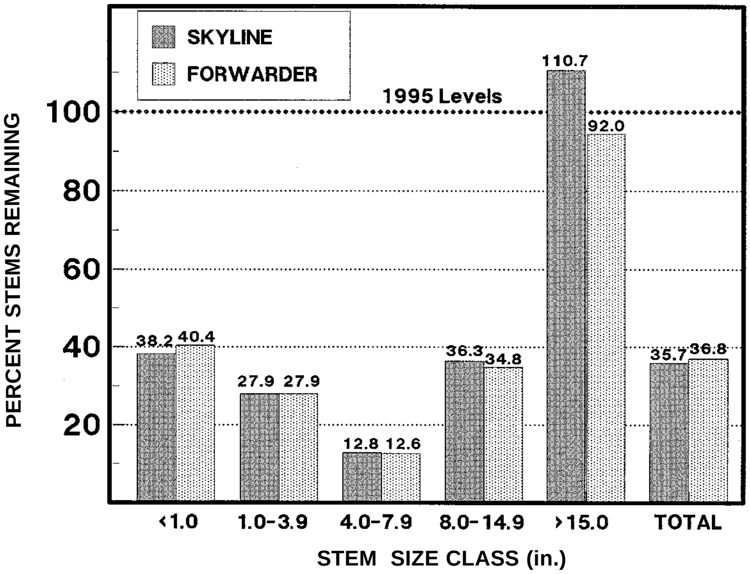

Figure 5— Mean percent stems remaining after treatment in five size classes for skyline and forwarder units at Limber Jim.

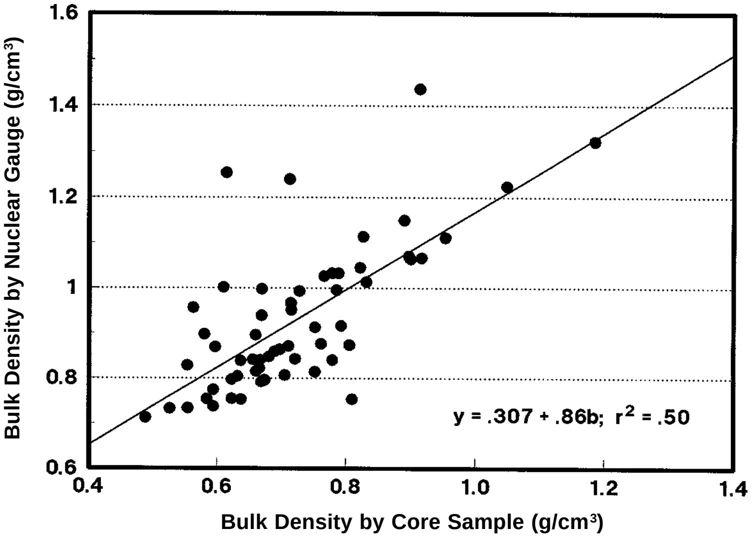

Figure 6 — Correlation between bulk densities taken by core sample and by nuclear gauge at the Limber Jim site (shape of regression significantly different from 0; P<0.0001)

compared to 2.0 acres compacted. Nearly all of the disturbance occurred in the logging corridors and skid trails, and in the three landings (units 4, 4a, 11a). In the fowarder units, wheel ruts were slightly more disturbed than the centers of the trails (39% vs. 30%), although this difference was not significant (P=0.34). We found 100% area disturbed in landings of skyline unit 4 and forwarder unit 4a, and in the trails used by the skidder in unit 6aN. Outside of the corridors, trails, and landings, only the skidder unit 6aN experienced detrimental disturbance (5%).

Of the seven experimental units, 6 had overall disturbance levels under 10% (Figure 7). The skidding unit (6aN) experienced 3.3 acres of disturbance, or 37% of the total disturbed acres. Although the forwarder units experienced slightly less overall disturbance than the skyline units (6% vs. 7%), these percentages were not significantly different (P=0.44). However, the type of disturbance experienced by the units differed depending on the type of retrieval system used: the skyline units showed a trend toward more displacement than the forwarder units (7% vs. 4%; P=0.13), while there was significantly greater compaction in the forwarder units (1.7% vs. 0.2%; P=0.03).

Objective 3: Production and Cost

Methods—The study compared three retrieval methods (forwarding, skidding, skyline yarding), each coupled with a single-grip harvester. Road access already existed at the Limber Jim site prior to project planning. Location of unit boundaries and tree marking were completed by the La Grande Ranger District (Wallowa-Whitman National Forest). No additional roads were constructed, so landings were placed on the perimeter of the units. For the forwarder and skidder units, trails were laid out as the loggers worked. For the skyline units, the logger premarked the skyline corridors (approximately 150 ft. spacing) and the trees for guyline attachment, tailhold, and for intermediate supports. Between the designated corridors, the harvester operators located the intermediate trails as they worked.

One type of single-grip harvester, forwarder, skidder, and skyline yarder were used throughout the study units. The harvester was a 1991 Hitachi 200LC excavator on a 10.5 ft. track fitted with a 1992 Keto 500 processing head attached to a 30 ft. boom. The tracked harvester placed cut and limbed logs in bunches along trails spaced 60 ft. apart within each unit. After processing a stem, the harvester placed tops and limbs on the trail, which created a woody mat to help protect soil from disturbance. Adjustments were made to the spacing and alignment of the trails to accommodate terrain features on the forwarder units and to allow positioning of the corridors for the skyline units. These same trails were used by the forwarder, skidder, and skyline yarder to retrieve logs. The forwarder was a 12-ton 1996 Valmet 646 mounted on six wheels with a Cranab 650X boom, operated by a single individual. The skidder was a 1987 CAT 518 grapple skidder, also operated by a single individual. Yarding was done with a Diamond D210 yarder with an Eaglet motorized carriage (Eagle Trucking Co., La Grande); logs were loaded onto trucks or into the chipper by a John Deere 690 Loader with a hydraulic grapple and heel boom. The skyline system was a six-man, two machine (yarder and loader) operation. In units where retrieval was by forwarder, log lengths averaged 16 ft.; by skidder, logs were cut to convenient lengths between 11 and 28 ft.; by yarder, average log length was 23 ft.

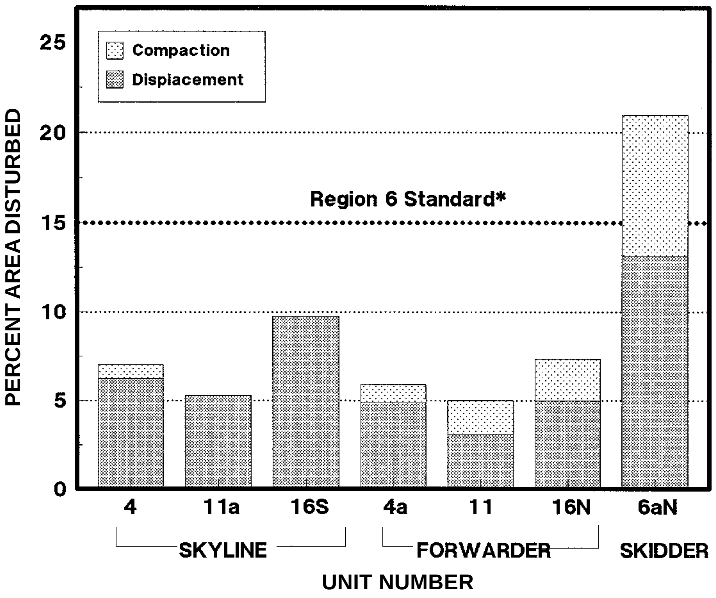

*Figure 7 — Percentage of soil area detrimentally disturbed among seven experimental units at Limber Jim. *Standard assumes 5% roads.*

Material removed from the seven stands was sorted into sawlogs or chip logs at the landings. Sawlogs were decked for later loading onto log trucks. Chip logs were processed on site with a 27 in. Morbark Chipper (CAT V-12 engine), with chips blown into chip vans for immediate removal. The chip buyer (Masonite) limited production to no more than 8 chip van loads per day, which did not constrain production in the research units. The trucking contractor charged a flat rate ($397/load) to haul from the site to the mill.

Study units were chosen to allow a fair comparison of three very different kinds of equipment combinations. Because skyline yarders typically are used on steeper ground and forwarders/skidders typically are used on flatter ground, an effort was made to choose study units that averaged intermediate in suitability for the three combinations. In reality, topography and woody structure of the various study units varied considerably both within and among themselves, and a critical assumption of the research is that these differences would balance out over the entire study area. The topography assumption was addressed on two site visits by researchers and managers (May and September 1995), and units were roughly classified as to suitable and unsuitable features. The woody structure assumption was addressed through careful examination of the pre-treatment stand exam and fuel data, and an effort made to identify the most suitable portions of units within which to conduct the operations research.

Operations occurred between June 20 and October 25 1996. The logging contractor filled out forms on time and production on a daily basis. Logging costs per scheduled machine hour were calculated using the owning costs (purchase price, depreciation, interest, insurance, property taxes), operating costs (maintenance, service, fuel, oil), and labor costs associated with the equipment and personnel used in the study. No allowance was made for profit or risk. Assumptions used for the estimation of costs and revenue are given in Appendix 1. Data were collected and analyzed by personnel from Oregon State University (James Doyal, Loren Kellogg) and the University of California at Davis (Erik Drews, Bruce Hartsough).

Results/Overall Patterns—A total of 91 acres were harvested as part of the study comparing forwarding and skyline yarding systems (Table 1). Average diameter of removed stems was 7 in., and comprised 55% down dead, 26% standing dead, and 19% standing live trees. In forwarder units, more logs (752 v. 611) and more tons (57.1 v. 48.1) were removed per acre. However, more sawlog tons per acre were removed in the skyline units (5.8 v. 3.5).

Cost and revenue will be expressed in terms of dollars per ton, as this factors out differences in the abundance, distribution, and type of material in the various units. Only the skyline and forwarder units will be compared: the single skidder unit (6aN) had cost estimates similar to the forwarder units, but data are considered unreliable because four different operators (with varying production rates) were responsible for retrieving logs in this unit, rather than the one experienced operator in the forwarder units.

Table 1. Material removed from forwarding and yarding units at Limber Jim.

	SKYLINE		FORWARDER	
	Total	Acre	Total	Acre
Chip Tons	1779	42.2	2639	53.6
Sawlog Tons	243	5.8	172	3.5
Total tons	2022	48.1	2810	57.1
Total Logs	25682	611.5	36997	752.0
Acres	42.0	----	49.2	----

Revenue was similar in the six forwarder and skyline units, with the skyline units yielding slightly more per ton than the forwarder units ($62.56/ton v. $60.97). This slight difference was due to the greater increment of sawlogs (66% higher) retrieved in the skyline units, either because the units themselves were of higher quality, or because loggers sorted for sawlogs more carefully in the skyline units.

Skyline units cost on average 74% more than forwarder units, largely because of differences in the costs of retrieval, processing, and layout (Figure 8). There was a 5-fold difference ($30/ton for the skyline v. $6/ton for the forwarder) in the average cost associated with retrieving the material from the woods to the landings, largely owing to the

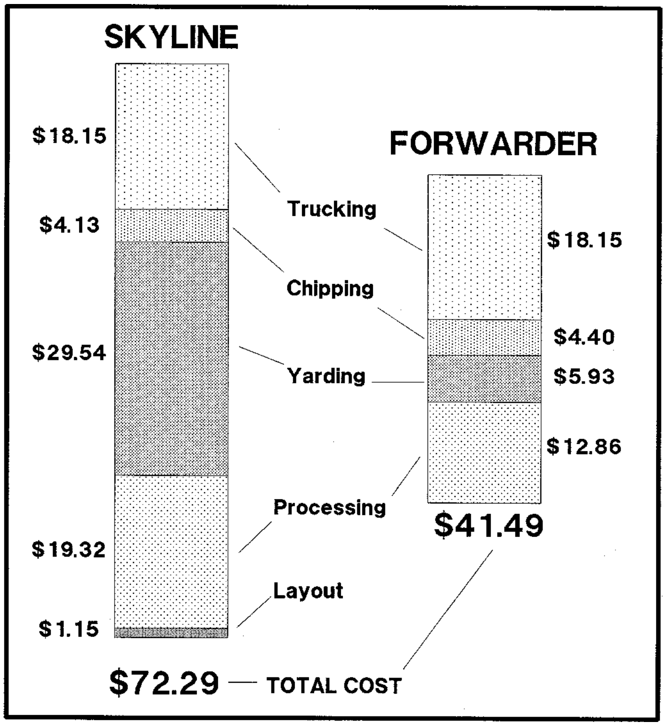

Figure 8 — Cost ($/ton) of skyline and forwarder retrieval systems, by catagory of logging activity. (Revenues were: $62.56/ton for the skyline system, and $60.97/ton for the forwarder system).

Note—The mention of specific equipment is not intended as an endorsement of brand or manufacturer.

need for a six-person crew in the skyline units, the greater equipment expense, and the higher production rate for the forwarder (13.5 v. 10.3 tons/hr). Processing costs were 50% higher in the skyline units ($19 v. $13), primarily because of the increased time needed to place logs for retrieval by the cable system. However, it is also possible that some of the 50% difference may have been due to the fact that more of the processing work was performed by a slower operator in the skyline units. While the forwarder units incurred no significant layout costs, the skyline units required an average of $1.15/ton for layout, which included corridor flagging, and tree marking for guyline, tailhold, and support trees.

Based on these figures, net revenues for the two systems differed substantially, with the skyline units experiencing a net loss of revenue (-$9.72/ton) and the forwarder units experiencing a net profit (+$19.47/ton). Overall, economically the project was a narrow success, at just over $10.00 per ton profit.

Among-Unit Variation— Since the study units represented a range of conditions (terrain, slope, layout; see Figure 1), it is worthwhile to address what general effect these variations had on yarding and stump-to-mill costs. In general, costs for the forwarder units were much less variable than for the skyline units. Stump-to-mill costs varied by only 8% for the forwarder units, but 36% for the skyline units. Similarly, yarding costs varied only 27% for forwarder units but nearly 86% for skyline units (Table 2). It is safe to say that the processor-forwarder system was relatively insensitive to variation in stand conditions, at least under the range of conditions observed at Limber Jim. In contrast, the skyline system proved to be very sensitive to variation in stand conditions, and therefore it seems most relevant to focus on understanding some potential causes for this.

The highest costs for the skyline system were observed in unit 4, in which yarding distances were short (270 ft. average), the yarding pattern was parallel, and the yarding direction was downhill. Short yarding distances require relatively more time for layout and for repositioning of equipment, especially when corridors are parallel. Yarding downhill typically requires the use of additional intermediate supports to maintain log suspension. By contrast, unit 16N was the least expensive skyline unit, largely because of the radial corridor pattern, the relatively longer yarding distances, and the uphill yarding direction. These differences resulted in a unit 16N cost of just $22/ton, compared to the unit 4 cost of $41/ton, a difference of 86% for these two skyline units. An intermediate cost was observed for skyline unit 11a, in which yarding distance was relatively long. Over a similar range of conditions, yarding costs for the forwarder showed nearly opposite patterns, with the lowest cost associated with unit 4a, and the highest cost associated with unit 16S. In particular, the relatively high cost of yarding in forwarder unit 16S was due primarily to uphill forwarding, and to the presence of numerous side trails (see Figure 1), which increased yarding time and decreased production. When the forwarder system is compared to the skyline system on a paired-unit basis, yarding costs vary from 3 times as expensive for the skyline system for units 16N/16S, to nearly 8 times as expensive for the skyline system for units 4/4a.

Table 2. Primary characteristics and logging costs ($/ton) of forwarder (4a, 11, 16S) and skyline (4, 11a, 16N) experimental units at Limber Jim.

UNIT	TREAT	AREA (Ac)	AVG/MAX YARD DIST (ft.)	AVG %SLOPE	YARDING PATTERN	YARDING DIRECTION	COSTS ($/ton)		
							Harv	Yard	STM[1]
4a	For	18.0	520/780	12	Parallel	Uphill	12.7	5.5	40.8
4	Sky	12.5	270/640	12	Parallel	Downhill	19.2	41.0	83.8
11	For	24.0	720/1070	2	Parallel	Flat	12.5	6.2	41.1
11a	Sky	23.0	510/1080	2	Parallel	Flat	20.8	27.0	71.4
16S	For	7.0	480/820	12	Parallel	Uphill[2]	14.5	7.0	44.2
16N	Sky	6.5	400/670	12	Radial	Uphill	15.7	22.0	61.5

1 Harv=Single-grip harvester; Yard=Yarding; STM=Stump to mill
2 Mostly uphill, with some downhill slopes of 12-25%

Finally, it is clear from Table 2 that although processing costs varied somewhat within both skyline and forwarder units, this variation was minor in comparison to the variation between skyline and forwarder units. For example, harvester costs for forwarder units varied from $13 to $15 (15%), and for skyline units from $16 to $21 (31%), but showed a 50% difference in mean unit cost between skyline and forwarder units (Figure 8). Hence processing cost is more sensitive to the type of retrieval system, than it is to variations in yarding pattern, distance, and slope.

DISCUSSION

In terms of fuel reduction, soil disturbance, and economics, Limber Jim met management objectives. Intermediate-size woody fuel (3-15 in. diameter), duff, and the number of stems per acre were each reduced to less than half of initial levels. Although small-diameter fuel slightly increased from initial levels, the overall fuel reduction by 50% across the sites changed the fuel conditions from fire behavior model 10 to model 8 (Anderson 1982). A surface fire in model 10 burns with greater intensity than a surface fire in model 8 and there is a greater potential for crowning, spotting, and torching because of greater quantities of 3 in. or larger limbwood (Anderson 1982).

Using the NEXUS fire behavior prediction system (Scott & Reinhardt, in prep), a hypothetical forest stand with a thinning treatment option similar to Limber Jim was assessed for crown fire hazard reduction. Active crowning in the nontreated forest was found to be initiated at wind speeds of 14 miles per hour, and sustained at wind speeds of 21 miles per hour. On the other hand, the treated stands with less fuel on the ground, greater spacing between trees, and lower crown density, would not be expected to experience crown fire initiation until winds reached speeds of 80 miles per hour, and would require wind speeds of 28 mph to sustain crown fire. This is a substantial reduction in crown fire hazard. However, because the Limber Jim units are small and separated by intact, non-thinned forested stands, the entire project area is probably only slightly more suitable now as an anchor for a fire-fighting effort. In general, perhaps the best use of mechanized harvest technology is to use it strategically across the landscape, creating a mosaic of stands with different fuel levels, such that subsequent wildfires will not encounter continuous fuels.

Maintaining healthy soil conditions is an obvious and well-recognized objective in land management. Among other things, soil disturbance by logging can have detrimental effects on variables that influence soil and stand productivity (Powers et al. 1990; Amaranthus et al. 1996), and can cause conditions that accelerate sediment delivery to streams (USDA 1980). Based on the regional standard (USDA 1996), operators at Limber Jim were able to maintain healthy soil conditions by keeping soil disturbance area under 10%. Compared to the skidder unit of the current study (20%) and to many previous studies using ground-based systems, this disturbance is relatively low (Froehlich et al. 1986, Geist et al. 1989, Lanford and Stokes 1995). For example, soil samples taken several years after ground-based harvesting on 11 timber sales in the Blue Mountains, indicated between 12 and 36% of the soil area in these projects was still in a damaged condition (Geist et al. 1989). Most of these projects involved whole-tree skidding, and it is clear that cut-to-length systems in which logs are retrieved either by forwarder or by skyline, will tend to cause significantly less soil disturbance.

While the 6-7% soil disturbance at Limber Jim is encouraging news to the land manager aiming to reduce impact, it remains to be seen how nature will mitigate even these low levels with time. The question remains: What are the long-term implications for site productivity of the 7% soil disturbance observed at Limber Jim? To answer this question, it will be necessary to monitor soils at Limber Jim for at least 10 years, to determine the extent to which natural processes mitigate the disturbance over the intermediate term. If the work of Geist et al. (1989) and others is any indication, we may need to be careful about planning multiple entries into stands, even if there is damage to less than 10% of the area per entry. If soil damage persists for long periods of time, managers may need to consider the need for designating a permanent trail system within some stands, in order to avoid excessive reductions in long-term productivity. Finally, since nearly all of the measurable soil damage at Limber Jim was confined to landings and machine trails/corridors, it is clear that short-term mitigation measures such as sub-soiling would be relevant only in those strata. Preliminary observations also suggest that most of the impact on trails occurred closest to the landings, further suggesting that sub-soiling (if it is done at all) may be relevant only on portions of trails experiencing multiple machine passes.

Under current funding guidelines, the timber sale remains the single most important tool for accomplishing management objectives on federal lands. Because of this, timber sales must provide an economically viable product mix that is compatible with management prescriptions. Additionally, since the mechanized harvest systems that may be needed for small-diameter work require a large capital investment at the outset, managers need to provide some assurance of the dependability of harvestable material, in order to expect contractors to buy and maintain the necessary equipment. At Limber Jim, despite high capital investment in equipment, the low percentage of saw log revenue (<20%), the relatively low prices of the chip market at the time of harvest, and the added burden of research needs, the purchaser was able to make a narrow profit. This is encouraging news for the federal land manager, because it means that fuel reduction objectives can be accomplished with timber sales, at least under certain conditions.

The comparison of log retrieval systems reveals that the correct blend of mechanized equipment is critical to insure project success. Under the circumstances presented at Limber Jim (relatively flat terrain, small, low-value logs), a single-grip harvester coupled with a forwarder is probably an ideal combination. Because the forwarder follows in the same track as the harvester, the latter machine does not need to take time to place logs in any particular way. On flat terrain, the forwarder's weight remains evenly distributed across its trail, and combined with slow operating speed (compared to a typical skidder), results in relatively low levels of soil compaction. Because the forwarder's grapple can lift bunches of logs, small log size presents little problem in terms of retrieval time. Given these considerations, it is not surprising that the Limber Jim project was an economic success, despite the low-value material removed.

By contrast, conditions at Limber Jim were generally not ideal for the skyline system. The need to have logs aligned toward the skyline corridors slowed processing speed of the harvester. Flat ground caused deflection problems for the cable system, and necessitated rigging intermediate supports, which took time. Piles of small-diameter logs were more difficult to grab, lift, and carry with the choker method of the skyline system. Only the relatively high skill of the skyline crew brought the cost of the skyline system down to where it did not cause an overall loss in revenue for the project as a whole. As shown with the Deerhorn project (McIver 1995, Brown and Kellogg 1996), a slightly higher sawlog component, or a slightly greater average log size would probably have made the difference in economic success using the skyline system at Limber Jim. Coupled with a moderate deflection, which would decrease the need for intermediate supports and substantially reduce soil disturbance, a skyline system would be a good choice if the management objective was to reduce soil disturbance to negligible levels. In general, conditions that would tend to favor the skyline system (large logs, steep slopes) would tend to disfavor the forwarder system, emphasizing the need for the manager to consider both economics and management objectives when planning a timber sale. As well, managers would probably benefit from a continued interaction with researchers to fine-tune the relations between stand conditions and harvesting methods, especially in economically marginal small-diameter stands.

Integrated, comparative studies of this kind, conducted in a management context, provide information that allows the manager to assess tradeoffs associated with the choice of particular management tools. When the three classes of information generated by the Limber Jim study are presented simultaneously, one can clearly see the balance of economic and environmental considerations (Figure 9). In this particular case, the manager's choice is clear: under the conditions presented at Limber Jim, choose the forwarder, because the increased expense of the skyline system does not buy you anything with respect to better fuel reduction or less soil damage. As mentioned, however, this outcome would likely be different under the type of conditions favoring the skyline system, such as larger logs and greater slopes.

Research at Limber Jim can best be viewed as an example of adaptive management, or "learning by doing." In this case, an operational experiment was designed to answer questions critical to the land manager. Information from the experiment was then provided to the manager in a timely manner, such that he or she could make a more informed decision in the next step of the management process. Although the level of experimental control and replication at Limber Jim has the potential to provide information of the highest quality and reliability, rigorous designs of this kind are not necessary to accomplish adaptive management. The single most important characteristic of a true adaptive management philosophy is the recognition of uncertainty in the management process. Managers can "learn by doing," by recognizing that any management practice or prescription has both certain and uncertain consequences, and that management cannot improve by ignoring the uncertain. The best way to deal with uncertainty is to compare management treatments undertaken in an operational context. Whether this is done with replication or control at any particular point is less important than is the process of comparison itself.

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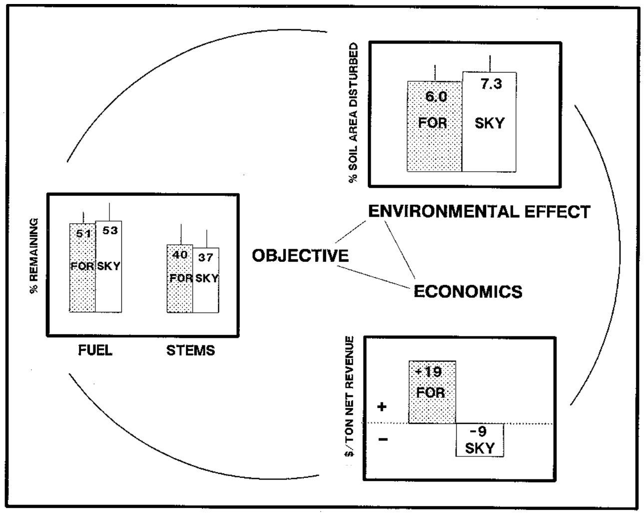

Figure 9—The three sets of information needed to make decisions on management tradeoffs: the OBJECTIVE, the ENVIRONMENTAL EFFECTS, and the ECONOMICS.

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APPENDIX 1

Machine Rate Calculation

To calculate the cost per scheduled hour for each machine, a standard approach, the Machine Rate Method was used. This method includes an approximation of the time-value of money and makes use of the following information:

Machine:
- new purchase price
- interest rate
- machine life
- depreciation
- salvage value
- maintenance and repair rate
- insurance rate
- taxes

Machine Operation:
- operating supplies (fuel, oil, etc.)
- annual hours of operation
- utilization rate (hours productively working/hours scheduled for work)

Personnel:
- wages
- labor overhead (vacation, workman's comp, benefits)

Values Associated with Each Machine

	Harvester	Forwarder	Skyline Yarder	Log Loader	Skidder	Chipper
Price ($)	235,000	194,000	407,000 [1]	250,000	160,000	260,000
Life (years)	5	5	5	7	5	7
Wages ($/hr)	19	18	142 [2]	17	18	17
Labor Overhead (% of Wages)	50	50	50	50	50	50
Total ($/SH)	114	80	230 [3]	73	72	93

[1] Includes cable yarder, rigging, and motorized carriage

[2] Wages for a six man crew

[3] Total yarding cost for the skyline system was $303 per scheduled hour, which combined the skyline yarder and the log loader costs.

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