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Cost and Productivity of New Technology for Harvesting and In-Woods Processing Small-Diameter Trees

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Abstract

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A study was conducted on the productivity and cost of an integrated harvesting and processing system operating in small-diameter timber (western hemlock-type) on the Olympic Peninsula of western Washington. The system uses a new steep-slope feller-buncher, a clam-bunk grapple-skidder (forwarder), a prototype chain-flail debarker-delimber, a chipper, a conveyor system, and a prototype shredder. The study showed that the system harvested and processed trees at a combined-system cost of $7.80 per green ton at a production rate of 455 green tons per day. The delivered product mix was 53 percent chips, 21 percent saw logs, and 26 percent hogged fuel by weight. The productivity and machine rate of each piece of harvesting and processing equipment and other data are given.

Keywords: Logging, whole-tree harvesting, feller-buncher, intensive harvesting, utilization, integrated harvesting, in-woods chipping, small-tree harvesting.

Summary

An integrated harvesting and processing system is operating in dense stands of small-diameter timber (western hemlock-type) on the Olympic Peninsula of western Washington. The stands are being clearcut to a 1-inch by 10-foot standard with an integrated system employing six pieces of woodland equipment, three of which are distinctly new. Trees are felled and bundled with a new steep-slope feller-buncher and carried to an in-woods processing system by a clam-bunk grapple-skidder (forwarder) where they are sorted and simultaneously processed into three products: saw logs, clean-pulp chips, and hogged fuel. A prototype, multiple-stem, chain-flail debarker-delimber prepares some stems for chipping. Bark, branches, trim ends, and very small trees not processed into saw logs or clean chips are lifted by a conveyor-grapple system into a prototype shredder, which processes all remaining woody materials into hogged fuel.

A study was conducted to quantify the operating parameters of the system, including production rates and costs of individual machines, the interdependency of equipment at the processing site, and the overall production cost of the system.

The study showed that the system harvested and processed about 300 green tons of products per acre from 2,300 standing trees per acre at a production rate of 455 tons per day and at a cost of $7.80 per green ton. The delivered product mix was 53 percent chips, 21 percent saw logs, and 26 percent hogged fuel by weight. Because the processing system produced three distinct products simultaneously, costs of operation could not be rigidly attributed to individual products. This integrated system was able to economically produce three separate products simultaneously from a stagnated stand of small-diameter trees, where single-product extraction had not previously been profitable.

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Background

Natural regeneration after a series of catastrophic fires, the latest in the mid-1920s, produced overstocked stands of small trees on the Olympic Peninsula in the State of Washington. About 20,000 acres of these stands are on the Quilcene Ranger District, Olympic National Forest. These stands, with average diameters of 8 inches and less, have stocking densities up to 40,000 stems per acre. Doghair[1] is a local term that has been used to describe these stands. These stands (fig. 1) are comprised primarily of western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*), and western redcedar (*Thuja plicata* Donn ex D. Don), and occasional large cedar snags.

Because of the overstocked conditions, growth in the doghair stands is well below normal. A goal of land managers has been to restore these stands to a more productive state. Conventional harvesting methods and equipment have been poorly adapted to the dense, small-diameter trees, and have resulted in inefficient handling of small trees, high costs, and low product recovery per acre. Stand-conversion alternatives have also proved to be cost prohibitive. It seemed unconventional means would be required to accomplish the objective of converting these stands to more productive conditions.

[1] See glossary for terms used in this report.

Figure 1—Dense stand of small-diameter trees in the study area near Quilcene, Washington. Harvesting stands such as this requires innovative technology and multiple-product marketing.

Early attempts to rehabilitate these stands were complicated by inadequate equipment for harvesting and processing, ineffective marketing for all potential products, and adverse environmental impacts, particularly soil compaction. In recent years, several timber operators have attempted to harvest doghair stands by using combinations of equipment and marketing options. These approaches, however, also proved to be unsuccessful because of inefficiencies in either harvesting, processing, or marketing. One timber operator devised a central, in-woods processing operation to take advantage of new technologies and whole-tree product marketing. In addition, innovations in felling and skidding stems to the in-woods processing operation were attempted and refined. The use of feller-bunchers and multiple-stem forwarding proved to be the most efficient and cost-effective means for delivering the trees to the processing center. A great deal of progress has been made in making better equipment and methods for handling and processing doghair stands. Equally important has been the successful marketing of all biomass components of these stands as saw logs, clean chips, and hogged fuel.

In 1983, the USDA Forest Service awarded a contract to Hermann Brothers Logging and Construction Company (1) to enable continued development and study of equipment and methods for economically converting stagnated stands of small trees to a productive status and (2) to provide the basis for a comprehensive study of the technology and economic feasibility of removing and using the products from small-diameter tree stands.[2]

In 1986, a grant from the U.S. Department of Energy (Bonneville Power Administration) through the Pacific Northwest and Alaska Bioenergy Program was awarded to Hermann Brothers to assist in the development of specialized equipment for producing biomass fuels from these overstocked stands.

In the past 4 years, the timber operator has developed and applied several arrangements of equipment in search of better harvesting and processing economy and efficiency. One specific need was a feller-buncher capable of operating on terrain steeper than 30 percent, thus extending the area available for timber harvesting. A new steep-ground feller-buncher was developed, with a self-leveling boom carriage that automatically stabilizes the operator's control cab on slopes up to 70 percent. Preliminary evaluations showed this machine to be faster and capable of operating on much steeper ground (80 percent) than other felling and bunching machines in use at the time. This feller-buncher, coupled with a clam-bunk skidder (grapple forwarder), has greatly improved the efficiency and economics of delivering small-diameter trees to the in-woods processing site. The timber operator has also used mobile cable yarders to bring trees into the in-woods processing system, where slopes have exceeded the slope capabilities of the clam-bunk skidder.

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[2] The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by either the U.S. Department of Agriculture or the U.S. Department of Energy of any product or service to the exclusion of others that may be suitable.

This report describes the cost and productivity of equipment systems observed during two related studies. The first study focused on the successful felling, bunching, and forwarding operations being used in the doghair stands on the Quilcene District. The second study addressed the operation of an in-woods, whole-tree-utilization system that was observed in fall and winter of 1986-87. The intent of the studies was to capture the comprehensive technical and economic information provided by application of this new technology to small-diameter tree stands. These studies were conducted simultaneously to share common elements.

This report provides information to evaluate a promising biomass-harvesting method and a basis for evaluating harvests of similar stands elsewhere in the region. As noted in a recent issue of *Biologue*, "The profitable conversion of small-diameter trees could result in significant increases in supplies of woody biomass for production of energy...a key element in the effective marketing of small-diameter trees" (Anon. 1986). Energy values from whole-tree chips are high (Howard 1987), providing an incentive to use biomass that would otherwise be left as residue. The proven ability to efficiently harvest small-diameter stands and multiple-product marketing will provide new opportunities to the land manager. Stands previously thought to be unmerchantable may now be considered in a different way. Potential sites for applying this technology include stands currently defined as precommercial size, having underused species (such as lodgepole pine and red alder), available for commercial thinning, and available for removal of smaller trees in a double-entry harvest system. Economics, and other factors, may still limit some applications. The ability to use all possible products in a stand in a cost effective manner, however, will affect the management and harvest of the region's second-growth timber.

Objectives

The objective of this effort was to characterize and quantify the operating parameters of the existing harvesting and processing system being used for stands of small-diameter trees. The effort is being made because of the need for a cost-effective stand conversion method. Potential multiple-product markets for the biomass harvested from these stands present an opportunity for increased revenue to aid the conversion of these stands.

Specific objectives of these studies were as follows:

1. Determine the quantities and types of wood products harvested and processed per acre from the doghair study area by the system.

2. Determine the costs and production rate of each piece of equipment used in the harvesting and processing subsystems.

3. Identify and sum the total costs ($) of owning and operating the harvesting and processing subsystems during the study periods.

4. Determine the total productive cost ($/ton) of harvesting and processing with this system as it produces the observed product mix.

System Description

Figure 2 illustrates the equipment arrangement and flow of materials from the stump through the in-woods processing system and onto trucks bound for market. The following sections describe each piece of equipment.

Harvesting System

Feller-buncher—A prototype steep-slope feller-buncher, model FB-1, developed by Washington Logging Equipment Company,[3] used to cut and prebunch the doghair trees (fig. 3).

[3] The FB-1 is currently manufactured and marketed by Allied Systems Company of Sherwood, Oregon, as the Allied Tree Harvester ATH-28.

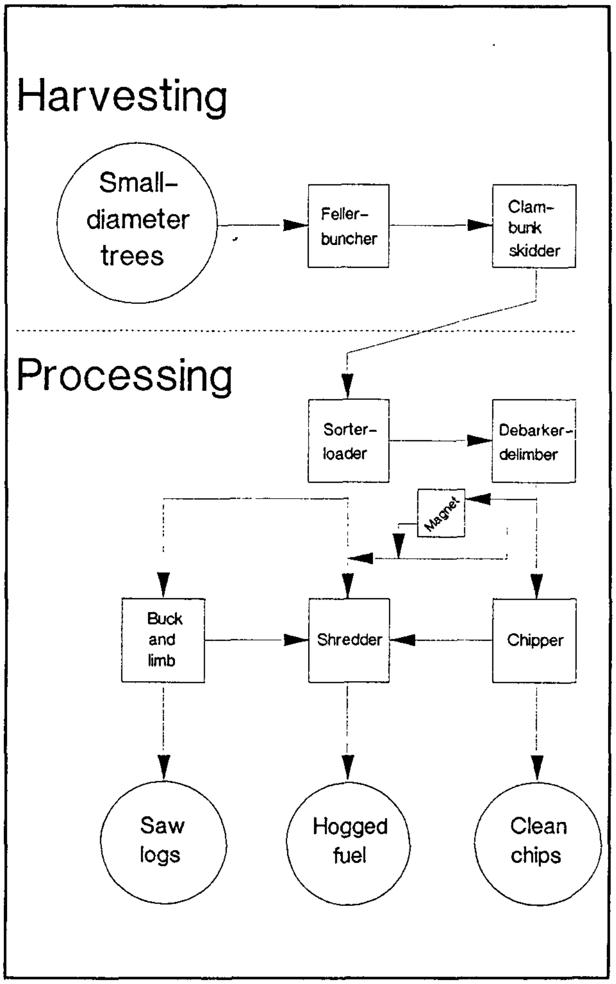

Figure 2—Equipment arrangement and material flows through the in-woods processing system for small-diameter trees.

Figure 3—Steep-slope feller-buncher prototype used during the study.

Forwarder—A rubber-tired clam-bunk skidder, Timberjack 520A, with a selfloading grapple, was used to transport the prebunched trees from the woods to the processing site (fig. 4).

Processing System

Several field trials of various combinations of equipment and material handling processes were tried with limited successes. Figure 5 shows an overview of the final central processing system being used on study site B. The system is arranged so that the trees to be processed arrive on one end, and the products are hauled away in trucks from the opposite end. The processing system consisted of the following specific equipment:

Figure 4—Forwarders that move large loads of small stems enhance the efficiency of harvesting dense stands.

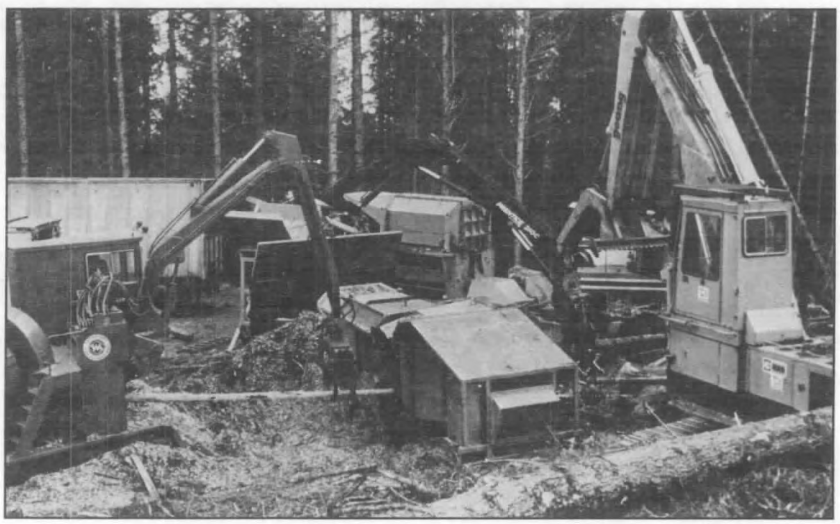

Figure 5—The central processing system, where all breakdown of products occurs.

Mobile loader—A self-propelled, Caterpillar 225, shovel-type loader (fig. 6) used to sort the trees and position them for processing. The loader was an integral part of the clean-chip operation, feeding trees through the "debarker-delimber" and into the reach of the grapple used by the chipper operator to feed the chipper. This loader moved several forms of woody materials to the shredder. The loader also loaded log trucks.

Debarker-delimber—A prototype chain-flail machine (fig. 7), built by Hermann Brothers, used to clean bark and limbs from multiple stems before chipping so that resulting chips would have relatively low bark content. The flail chains were mounted on twin vertical shafts.

Figure 6—The mobile loader, which handles all materials arriving at the landing.

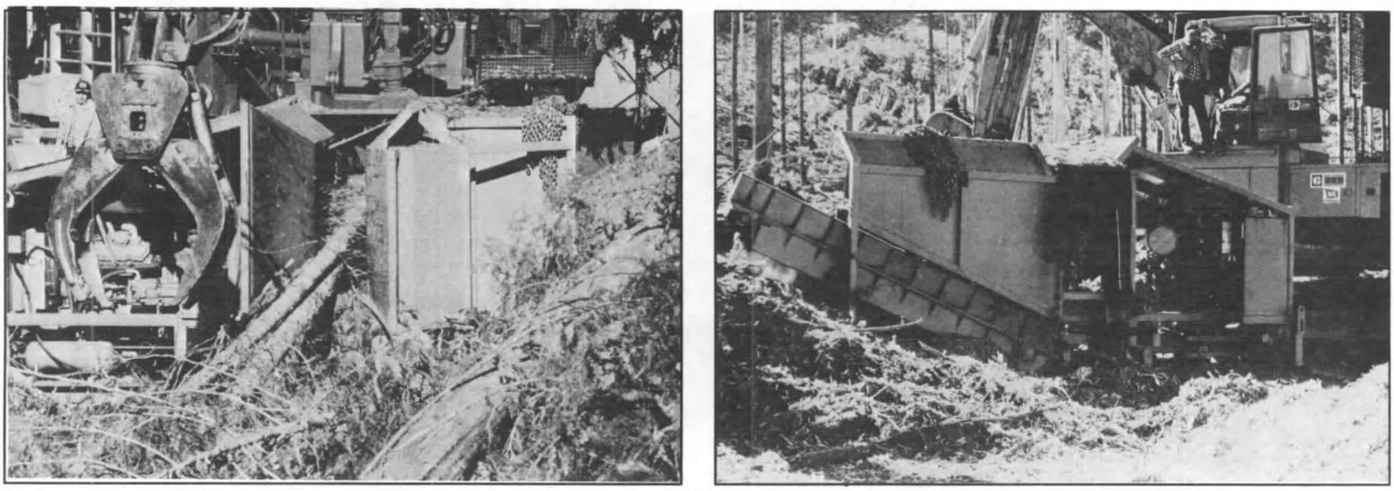

Figure 7—The debarker-delimber processed trees that produced clean chips and hogged fuel.

Chipper—A Morbark Chiparvester with a 23-inch in-feed opening used for processing the debarked trees into clean chips (fig. 8).

Shredder—A prototype machine with a drum chipping head and a built-in Prentice loader used for processing the smaller trees, the bark and limbs from the debarker, the limbs and trim ends from the saw log operation, and all other subgrade material on the landing into hogged fuel (fig. 9).

Figure 8—The chipper produced clean chips from stems that had been debarked and delimbed.

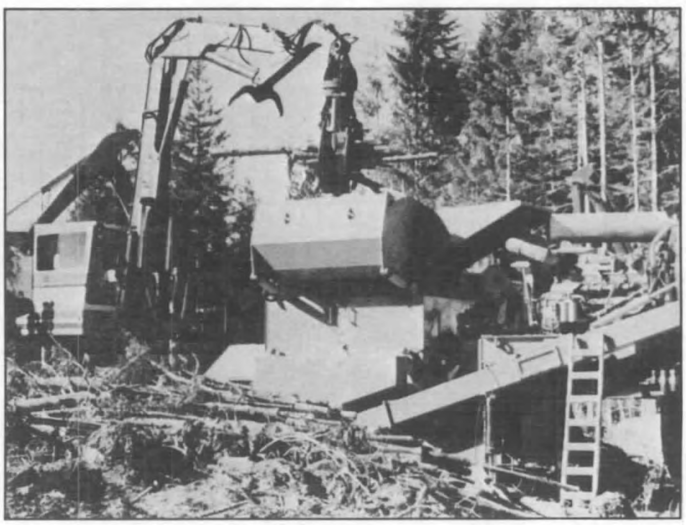

Figure 9—The shredder processed all materials not sold as logs or chips.

Conveyor-magnet system—A hydraulically driven conveyor system used to handle the bark and limbs that were expelled from the debarker-delimber (fig. 10). The conveyor system sorted the woody debris into three size categories: (1) large, heavy limbs; (2) small limbs; and (3) fine materials. Both categories of limbs were piled within reach of the shredder grapple, which periodically lifted the piles and loaded them into the shredder in-feed bin. The fine materials were lifted by another conveyor and dropped across an inclined magnet, which was designed to trap ferrous materials and prevent them from damaging the cutting teeth inside the shredder.

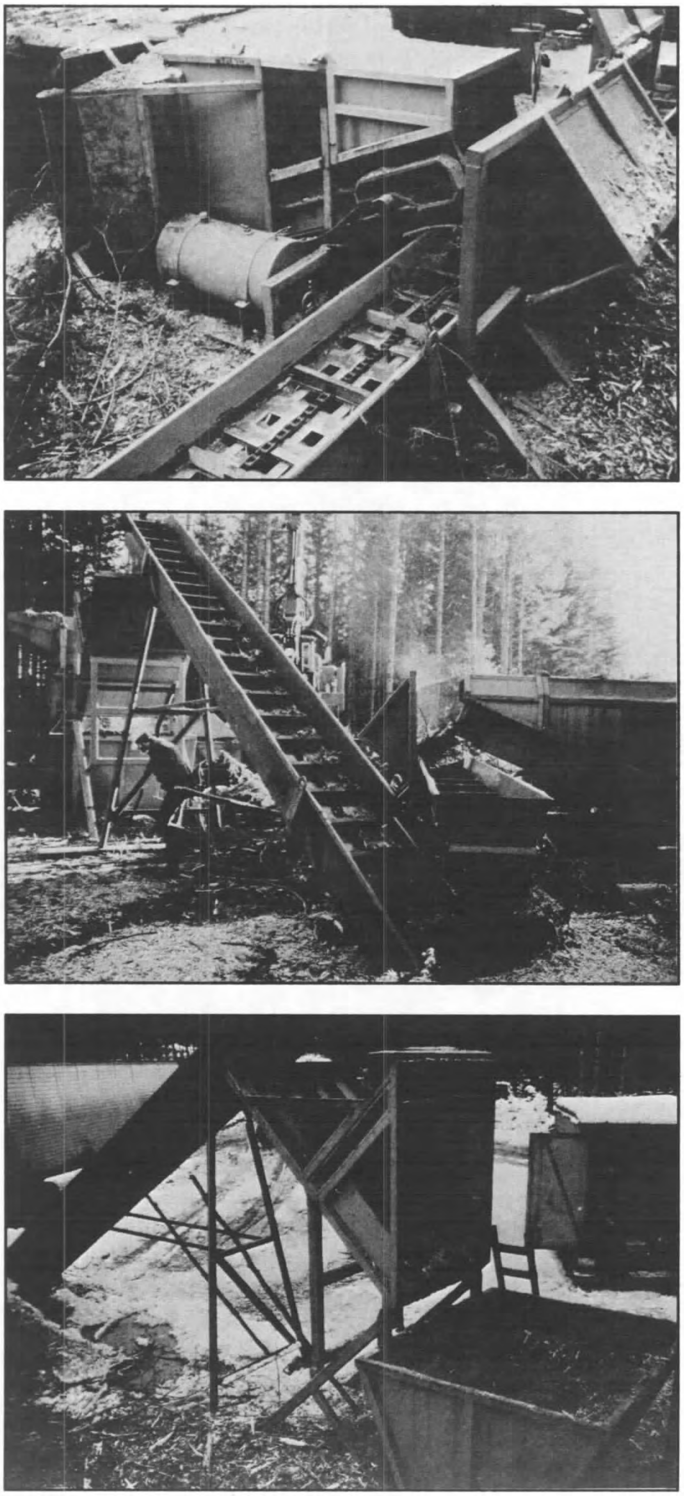

Figure 10—The magnet-conveyor system.

Support System

Road and landing construction equipment—A variety of equipment used in many capacities and for different lengths of time to prepare and maintain the landing at the processing site and the road that leads to it. Items in this category included earth-moving trucks, front end loaders, bull dozers, and motor graders. In the current operating system, approved by the Quilcene District, a large (D-6 size) tractor is used after harvest for ripping the soil on heavily traveled paths, such as the "go back" road used by the forwarder.

Maintenance equipment—Service vehicles with welders, hoists, and spare parts used to maintain the processing equipment in operating condition. Fuel and oil vehicles were also used.

Crew transportation—A six-passenger pickup truck used to transport the work crew to the work site each day.

Study Methods

Two study blocks were selected for whole-tree harvesting during this study. Cost and productivity information was recorded while the prototype harvesting and processing system operated normally in the study area. Trees to be harvested were preinventoried by using conventional stand exams. Processed products were weighed as they were taken out of the area. This put production data on a green-weight-per-unit-time basis. Cost information was on a dollar-per-productive-hour basis. This resulted in productive costs being expressed in dollars per green ton.

A steady-state operation was observed, free of any transitory effects of equipment set-up or move-out. Each study block was completely harvested during the respective harvest period. Study of processing was done concurrently with the study of harvesting so the same stand could be observed from the start of felling to the end of processing. Simultaneous studies simplified the field work because stand exams and truck weighing applied to both studies. Furthermore, all nonstudy materials were removed from the processing site before each study period so that only trees from the marked study blocks were processed.

Area Selection

The study area, on the Quilcene Ranger District, Olympic National Forest, consisted of 3.12 acres (block A) plus 3.48 acres (block B) of small-diameter trees within a timber sale (Doghair Unit 79) that was under contract for harvest and site conversion during the study. Both study blocks had similar stand density and terrain. Slopes ranged from 20 to 35 percent. Each block was selected so as to allow a single forwarder to keep the processing equipment busy. An additional forwarder was sometimes used by the operator to cover longer distances, however. The blocks were laid out in roughly rectangular shapes for convenience in marking and harvesting. Figure 11 shows the location of the study area.

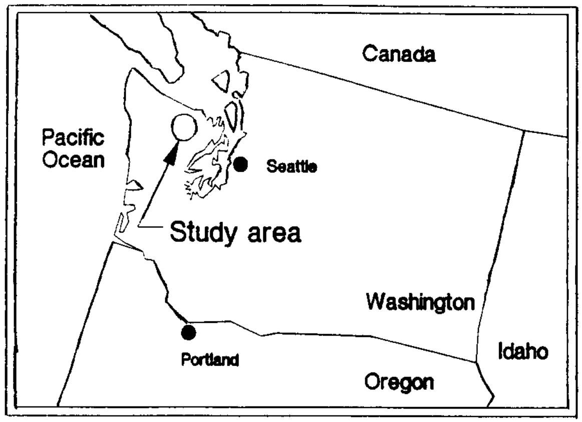

Figure 11—Location of the study area near Port Angeles on the Olympic peninsula of western Washington.

The soils underlying these overstocked stands are Entisols and Inceptisols that developed on deposits from continental glaciers (Jennings and others 1982). Generally, these geologic materials differ in particle size and shape, strata orientation, degree of compaction, and resistance to weathering. The soils are weakly developed, lacking structure and differentiation of horizons; this has resulted in soils that are highly variable even within small areas of similar relief. Many of the unstructured subsurface layers are impermeable and seem deficient in nitrogen (N) and some micronutrients such as copper (Cu) and iron (Fe) with perhaps toxic levels of manganese (Mn) (Little and Waddell 1987).

Stand Inventory

The number and size of trees in each study block were determined by a routine stand-exam procedure. On each block, twelve one-fiftieth-acre circular plots were systematically laid out. All standing trees in the plots, living and dead, were inventoried by 1-inch diameter classes and species. Diameters at breast height of all sample trees were recorded, and heights of three randomly selected trees in each diameter class were recorded. The ground slope was measured, and terrain roughness was assessed. An estimate of the total number of trees by diameter class for each block was computed from these data.

Time and Production Measurements

Observations were recorded during harvesting and processing to provide data from which estimates of production rates for each piece of equipment in the system could be made; this required observations of the operation of each piece of equipment. Operational-time components were recorded for all equipment throughout the study. In addition, more detailed observations that included production information such as number of pieces handled were made on each machine during several randomly chosen, intense, hourly sample periods. Table 1 shows the intense observation time for each machine on each study block as a percentage of the total operating time. Time elements and units of production were recorded as described below.

Table 1—Observation time as a percentage of total operating time for each machine by study block

Machine	Block A	Block B
	Percent	
Feller-buncher	100	28
Forwarder	25	26
Sorter-loader	22	100
Debarker-delimber	100	100
Chipper	18	100
Shredder	100	100

Time measurements—For each piece of equipment, an on-site observer recorded time in the following categories:

Time category	Definitions
Scheduled time	Total planned work hours that each piece of equipment was assigned to the job. Also, the sum of all time components: that is productive, idle, delay, and down times (total operational time).
Productive time	Hours when equipment was working at the assigned task(s).
Idle time	Time when equipment was ready to be productive but could not process material because none was available from the previous process (no workload).
Delay time	Time when equipment could not complete material processing because the subsequent process was fully loaded and could not accept new material (bottleneck ahead).
Down time	Time when equipment was unavailable for productive work because of scheduled or nonscheduled interruption of processing due to mechanical or operator inability to proceed.

Figure 12—Total green weight of all products was found by weighing all trucks on portable scales.

Production measurements—Production of the harvesting and processing system was measured in units of green weight (tons). Weight units are preferred to other units such as cords, board feet, or even cubic feet for biomass measurements because all forms and parts of the tree can be consistently accounted for by weight. Very small trees cannot be measured by existing board-foot rules, and no other measurement adequately tracks limbs and tops. Also, many wood-handling systems are limited in how much weight they can lift, and equipment designers and operators can be more effective when they know how much actual weight is to be handled. Weight units can readily be converted to other units of measure when needed to aid communication. If desired, green weight may be adjusted for moisture content to reflect wood weight at a different moisture content, such as bone-dry units.

For this study, all products being taken from the processing site at the landing were weighed on portable truck scales (fig. 12). Each truck was weighed, both loaded and unloaded, so that the product net weight could be determined. The portable-scale results were corroborated with mill scales where the products were delivered. The net weights of each product were summed to give the individual production of logs, chips, and hogged fuel. The weights of all products were then summed to give the aggregated production (multiple-product yield) from the study blocks. Because the landing was cleared before and after each study period, the assumption was made that the total product weight[4] was equivalent to the weight of all trees handled by the feller-buncher and subsequently by the forwarder and also the mobile loader. Similarly, the weight of all chips was the production of the chipper and the debarker-delimber. The total hogged-fuel weight was the production of the shredder, and the production of saw logs was equal to the weight of the logs that were hauled out on log trucks.

[4] Moisture loss was assumed to be negligible during the harvesting and processing activities. Moisture is lost, however, because trees continue to transpire moisture when felled and left on the ground with their crowns intact. Moisture also evaporates during the chipping and shredding operations (as witnessed in visible evaporation from warm chips in freshly loaded vans). The extent of moisture loss from these sources is unknown.

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Continue

Cost and Machine Rate Determinations

The cost of harvesting and processing these small-diameter trees was an important part of the study because the economics of stand conversion by using the central processing system and multiple-product marketing affects how and where the system may be applied.

A machine rate was calculated for each piece of equipment. The machine rate is defined as the hourly cost of ownership and operation for a machine or process, including investment amortization, consumables, and labor costs. The machine rate is based on a productive hour. This takes machine reliability (availability) and usage rate (ratio of productive time to scheduled time) into account. Costs of ownership (Mifflin 1980) were calculated for each piece of equipment, based on factors such as original investment, interest rates, salvage value, depreciation period, taxes, and insurance. Similarly, operating costs, including fuel and oil consumed plus labor and supervision expenses, were also calculated for each piece of equipment.

Productive costs of each machine were calculated by dividing machine rates by the corresponding production rates. Total productive costs of owning and operating the harvesting system were calculated by summing the productive costs of the two machines of that system. For the harvesting system, however, the productive costs of the individual machines are not additive because each machine processes a different percentage of woody materials; therefore, the productive cost of the processing system was calculated by summing the products of the productive cost of each machine and the quantity of materials handled by that machine, and then dividing that sum by the total weight of all woody products delivered. This is equivalent to dividing the total cost of all operations by the total weight of all products from the system.

The following computation methods and equations were used to calculate the values needed to satisfy the objectives of this study:

Production rates for each harvesting and processing operation were calculated by dividing the total production of each operation by the total productive time spent to do that operation during the study.

Machine rates for each piece of equipment were calculated with the equations below.

The productive-time ratio of each machine was calculated by dividing the productive time of each machine by the scheduled time for that machine.

Machine availability was calculated from the equation below to quantify the reliability of the equipment during this study.

The productive cost for the total harvesting and processing system was calculated by dividing the total cost of all operations by the total weight of all products loaded onto trucks or vans for delivery to market.

Computation equations follow:

$$\text{Productive time (p-hr)} = \text{scheduled time} - \text{(idle, delay, and down times)}$$

$$\text{Productive time ratio (\%)} = \frac{\text{productive time}}{\text{scheduled time}} \times 100$$

$$\text{Machine availability (\%)} = \frac{\text{(scheduled time - down time)}}{\text{scheduled time}} \times 100$$

$$\text{Production rate (tons/p-hr)} = \frac{\text{tons of material processed}}{\text{productive time}}$$

$$\text{Ownership cost (\$/s-hr)} = \frac{\text{total annual ownership costs}}{\text{scheduled hours per year}}$$

$$\text{Operating cost (\$/p-hr)} = \frac{\text{hourly crew wages} \times (1 + \text{supervision rate})}{\text{productive time ratio / 100}} + \text{hourly fuel cost} + \text{hourly oil cost}$$

$$\text{Machine rate (\$/p-hr)} = \frac{\text{(hourly ownership cost)}}{\text{(productive time ratio)}} + \text{hourly operating cost}$$

$$\text{Productive cost (\$/ton)} = \frac{\text{(machine rate)}}{\text{(production rate)}} = \frac{\text{(total cost for job)}}{\text{(total production)}}$$

System cost ($) = sum of (productive cost × production) for all equipment and personnel used in the system

$$\text{System productive cost (\$/ton)} = \frac{\text{system cost}}{\text{total tons of product}}$$

Results and Discussion

Equipment Development

Several new pieces of equipment were designed and constructed to complete the prototype harvesting and processing system. In fact, four of the major components of the system were operated as first-of-their-kind prototypes. They are as follows:

1. Steep-slope feller-buncher
2. Multiple-stem debarker-delimber
3. Shredder
4. Conveyor-magnet system

The FB-1 steep-slope feller-buncher was delivered to the study site by the manufacturer about 6 months before the study for operator training and initial trials of the machine. When the study began, the operator seemed to be proficient, and the machine was functioning with a high degree of reliability.

A prototype debarker-delimber for multiple stems (designed and built by Hermann Bros.) was used during the study. This machine uses chain-flails to remove bark and limbs. Chains were mounted on twin vertical shafts. The debarker-delimber had no built-in feed system. Feeding was accomplished by the mobile loader in conjunction with the grapple of the chipper. The mobile loader passed trees through the chain-flails until they exited the debarker-delimber within reach of the chipper's grapple, which grasped the cleaned stems and fed them directly into the chipper's feedworks.

The biomass shredder was also designed and fabricated by Hermann Brothers. It was put into service on the study area about 3 months before the study.

The magnet and its collecting bin were built and added to the processing system at the beginning of the processing study on block A. The debris conveyor system was introduced to the processing system a few days before the beginning of the study on block B. This support equipment was also designed and fabricated by the Hermann Brothers from commercially available components. The processing system was moved onto the prepared landing and was ready for production in about 2 hours. Each landing was about one third of an acre and was adjacent to a lower corner of a study block. Materials from about 40 acres of doghair stands were handled on each landing.

Stand Inventory

Table 2 lists the population of trees on each study block by diameter class. About half of the trees on each block were dead. The living trees were comprised of western hemlock (33 percent), Douglas-fir (28 percent), redcedar (22 percent), true fir (16 percent), and alder (1 percent). About 78 percent of the trees on block A and 85 percent of the trees on block B had diameters of 6 inches or less. The stand inventory showed that block A contained 1,642 stems per acre and block B contained 2,283 trees per acre. A statistical analysis showed the standard error of the mean to be 151.8 trees per acre (9.3 percent) on block A and 200.7 trees per acre (8.8 percent) on block B. The mean stand diameter for all trees on both blocks was 4.1 inches. The canopy was closed with a typical live tree height of about 95 feet. This stand characterization is given to help compare doghair stands to stands in other areas.

During the study, most of the smaller, dead trees were not delivered to the processing site. Because of the extent of decay, they usually broke into short pieces during the felling process. Adjusting the stand exam for this situation by excluding dead trees under 4 inches, the estimated number of trees processed from block A was 896 per acre and 1,241 trees per acre from block B.

Products

All trees taken from the study blocks were transported to the sorting and processing site at the landing. Materials were not allowed to accumulate at the landing. Depending on their size and quality, the trees were processed into three different products: saw logs, pulp quality chips, or hogged fuel (table 3).

Table 2—Number of stems per acre by diameter class for study blocks A and B

Diameter class	Block A			Block B		
	Live	Dead	Total	Live	Dead	Total
Inches	*Number of stems per acre*					
1	25	*271	296	104	*654	758
2	38	*304	342	167	*288	455
3	62	*171	233	179	*100	279
4	121	50	171	129	54	183
5	96	25	121	100	25	125
6	121	4	125	125	12	137
7	42	—	42	58	—	58
8	71	—	71	33	—	33
9	29	—	29	38	—	38
10	62	—	62	38	4	42
11	25	—	25	25	—	25
12	50	—	50	21	4	25
13	17	—	17	8	—	8
14	21	—	21	21	4	25
15	17	—	17	17	—	17
16	—	—	—	29	—	29
17	4	—	4	25	—	25
18	—	—	—	17	—	17
19	—	—	—	—	—	—
20	4	4	8	—	—	—
21	—	—	—	—	—	—
22	4	—	4	4	—	4
23	4	—	4	—	—	—
Total	813	829	1,642	1,138	1,145	2,283

* Most dead stems under 4 inches in diameter were left in the woods
— = No trees of that diameter observed in stand exams

Table 3—Product distribution[a] from study blocks by green tons per acre and percentage

Product	Block A		Block B	
	Tons/acre	Percent	Tons/acre	Percent
Saw logs	45	16	60	21
Chips	147	53	157	53
Hogged fuel	84	31	76	26
Total	276	100	293	100

[a] No particular merchantability specifications were imposed on this system. This permitted the operator to adjust the product output to follow the market-dictated highest and best use on a near daily basis.

Table 4—Nominal daily production of the doghair harvesting and processing system

Product	Block A	Block B
	Truckloads/day[a]	
Saw logs	2	3
Clean chips	7	9
Hogged fuel	4	4

[a] Based on 10-hour workdays, 25 tons per log truck, 20 tons per chip or hogged-fuel van.

Production Rates

The overall-system-daily production rates are shown in table 4. These average rates are based on 10-hour workdays and net product weights of 25 tons per log truck and 20 tons per chip or hogged-fuel truck.

Table 5 summarizes the production rates of the harvesting and processing equipment on each study block. Note that the production rates refer to the individual pieces of equipment and not to the products or to the material-handling processes. The production rates of all equipment were higher on block B than on block A. Progress on a learning curve may have had a slight effect, and there were more trees and slightly larger trees on block B, but the main contributor to higher production rates was the addition of a conveyor system to the processing system at the landing. As materials flowed through the landing faster, the forwarder was able to deliver trees faster, thereby making more efficient use of its productive time. The time spent by the forwarder in roadway improvements also contributed to a higher production rate on block B.

Table 5—Production rates of harvesting and processing equipment on each study block

Machine	Block A	Block B
	Tons/p-hr[a]	
Harvesting equipment:		
Feller-buncher	55	60
Forwarder	46	65
Processing equipment:		
Sorter-loader	30	42
Debarker-delimber	29	34
Chipper	29	34
Shredder	10	10.5

[a] Tons = green tons; p-hr = productive hour

Harvesting—The FB-1 (ATH-28) steep-slope feller-buncher was used to mechanically fell and simultaneously bunch the trees on both study blocks. Block A was felled in November 1986; block B was felled in January 1987. Forwarding was done entirely with a single forwarder (clam-bunk skidder, Timberjack 520A). Forwarding was done simultaneously with the processing operation, about 1 week after felling each block.

Cutting—Felling and bunching with the steep-slope feller-buncher progressed efficiently and effectively with the machine working both uphill and downhill. Butts of the trees were placed downhill for easy loading by the clam-bunk skidder. Because less rotation of the felling boom was required when working uphill, the production rate of the feller-buncher was about 40 percent higher on the uphill passes. The independently pivoting, quad-track drive system of the feller-buncher gave it excellent mobility over uneven terrain on all slopes encountered, which ranged between 20-35 percent in the stand and up to 60 percent in short stretches. The automatic leveling feature of the feller-buncher boom platform functioned well, keeping the operator from working in unnatural positions and allowing him and the machine to operate consistently and smoothly. The machine had high ground clearance (almost 3 feet), which enabled it to pass easily over many ground obstacles that would have impeded travel of most woods machinery. The effective reach of the cutting head was about 60 feet from one side to the other, compared to a cutting path of about 40 feet by the conventional feller-bunchers used in the area.

The production rates of the feller-buncher on this test were 55 and 60 tons per productive hour, respectively, on blocks A and B. Based on data collected during the intense, hourly sample periods, the corresponding production rates in number of stems per productive hour were 195 and 225. The overall production rate on an area basis was 0.20 acres per productive hour on both blocks A and B. The feller-buncher averaged 2.27 stems per cycle on block A and 2.24 stems per cycle on block B. A limited observation (1 hour only) of relative production rates of uphill vs. downhill operation during the study on block B showed that the feller-buncher cut and bunched 124 cycles per productive hour during uphill operation and 87 cycles per productive hour during downhill operation. A cycle is defined here to be the felling, rotating, and bunching movements of the machine. A cycle was counted each time the trees held in the shear head were released onto the ground or a bunch. Table 6 shows the distribution of piece count handled by the feller-buncher on each cycle. Over 40 percent of the cycles handled only one tree, and 80 percent of the cycles handled three or fewer trees.

The number of stems harvested, based on the observed production rate, was 9 percent higher than the number of trees based on the adjusted stand exam on block A and 13 percent lower on block B.

Table 7 summarizes the operational-time components of the feller-buncher on each study block. The 8-percent downtime on block A consisted of 34 minutes to replace a broken hydraulic hose on the felling head, 17 minutes total for checking and bleeding lines, and 34 minutes for operator breaks.

Table 6—Distribution of number of stems cut and bunched per turn by the feller-buncher

No. of stems per turn	Frequency	
	Block A	Block B
	Percent	
1	41	43
2	25	21
3	14	16
4	11	10
5-8	9	10

Table 7—Operational-time components for the feller-buncher

Time component	Block A	Block B
	Percent	
Operational time:		
Productive time	91	99
Idle time	0	0
Delay time	1	0
Down time	8	1
Total	100	100

Forwarding—The forwarder (clam-bunk skidder) was used to transport the trees from the felling and bunching sites of each study block to the roadside landing, where they were processed for transportation to market. Block A was forwarded in November 1986; block B was forwarded in January 1987. A typical turn of about 50-70 trees arrived about every 18 minutes on either block. The forwarder usually climbed to the top of the block and then loaded trees from the prearranged bunches as it headed back downhill towards the landing. The operator swiveled his seat around backwards to drive the machine in reverse or to operate the loading grapple. Traveling toward the landing, the operator faced forward, stopping occasionally to add logs to the bunk as the load straightened and settled during travel. Periodically, the operator would close the clam jaws to compact the load. The clam-bunk jaws would be closed when the load was complete, and the operator would continue to drive downhill toward the landing. This driving would straighten and further compact the load as the trees were pulled into the roadway, behind the forwarder, often making room for even more trees to be loaded onto the bunk. After the bunk was full, the operator would typically hold one or more larger trees in the loading-grapple jaws as he continued toward the landing. Once at the landing, both grapple and bunk jaws were opened, and the forwarder would drive ahead, allowing the trees to fall onto the ground within reach of the mobile loader. The forwarder seemed to perform its work smoothly and efficiently. It accomplished the forwarding operation on both study blocks without difficulty. The machine seemed to have adequate power and traction to climb the slopes on the study blocks. It also had sufficient power to lift the butt end of any tree and sometimes as many as 10 trees as it positioned them onto its bunk. It had sufficient agility and maneuverability to access the prebunched trees, while negotiating over and around many large culls and stumps. Forwarding with a clam-bunk skidder seems to be limited by uphill gradeability to slopes under 50 percent. Cable yarders (also used by Hermann Brothers in doghair stands) could reach trees bunched by the steep-slope feller-buncher on slopes greater than 50 percent.

The forwarder was also observed in use as a road-building device. On major skid roads that required multiple passes by the forwarder, the forwarder was used to lay small limbs and tree tops into surface depressions to minimize mud holes and soil compaction.

Observed production rates of the forwarder on this test were 46 and 65 tons per productive hour, respectively, on blocks A and B. Corresponding production rates in units of stems per productive hour were 161 and 244, based on earlier stem counts going into the prebunched piles. The production rate on an area basis was 0.17 acres per productive hour on blocks A and 0.22 acres per productive hour on block B. This production rate approximated the production rate of the feller-buncher, for the skidding distances of this study. The two machines worked well together in this respect. The feller-buncher operator always positioned the prebunched piles of trees with the maximum convenience of the forwarder operator in mind, that is, semi-herring bone fashion with the butts downhill. Harvesting sequence and travel routes were carefully planned by the operators and coordinated with the material flow needs of the processing system.

While study observations were being made, the forwarder provided a continual flow of trees for the processing system at the landing. The operator used slack demand times for nonproductive activities such as road maintenance, hydraulic hose replacements, and lunch breaks. The forwarder operator was observed to pace arrival times at the landing according to the stockpile of unprocessed trees. This was done by varying the route and distance traveled to load trees. When the stockpile was high, the forwarder loaded trees from the far end of the study block, bypassing some closer trees, which could later be quickly forwarded on demand when the stockpile was low. The operator also regularly bypassed some larger trees that were close to the landing to save them for times when a heavy load was needed at the landing. The larger trees were also used as load binders on top of bunks filled with many smaller trees. This practice secured the load for travel and improved the load density in the clam bunk.

The production rate of the forwarder is sensitive to the required travel distance. If the cutting unit were quite close or next to the landing, the forwarder could be expected to move trees faster than the feller-buncher could fell and bunch them; thus, the production rate of the forwarder might far exceed that of the processing system at the landing. On the other hand, as the travel distance increases, the forwarder would be slower than the feller-buncher; in this case, additional forwarders might be used to balance the harvesting operation so that trees arrive at the landing at the proper frequency to minimize idle time and delays of other processing equipment. For example, the average forwarding distance for each block during this study was about one quarter mile, and the forwarder spent roughly half of its productive time traveling. If the forwarding distance were doubled to one half mile, then the relative time spent traveling would increase to 67 percent, and the production rate could be expected to decrease to about two-thirds of the previous rate.

Table 8 illustrates the operational-time components of the forwarder on each study block. The information for block A is from a complete time-study log kept by an observer during the entire study period. The information for block B is based on observations made during the hourly (random) sample periods. On block B, the time spent doing other work (primarily road building along the haul route) seemed effective in improving the production rate of the forwarder, because even though a smaller percentage of operating time was spent as productive time, a higher production was achieved on block B. The forwarder experienced occasional delays at the landing, waiting for the loader to sort and clear previous incoming loads of trees. There were fewer such delays on block B because the landing-processing system was more efficient and predictable. Most of the downtime was caused by worn hydraulic hoses on the grapple boom. The operator replaced three of these while loading trees.

Table 9 shows the relative proportions of productive time the forwarder used to do separate functions on each of the study blocks. The information is based on observations made during the hourly (random) sample periods. A higher proportion of time was spent traveling on block B because the ground was wetter and softer in January on block B than it was in November on block A. The forwarder was used 75 and 57 percent of the time on blocks A and B, respectively. This reflects unplanned downtime and use of the forwarder for operations other than forwarding (principally road building and maintenance on block B) during the harvest. Most of the road-building time can be attributed to the study being conducted during winter months.

Processing—Observations made during the study resulted in measurements of production rates (in tons per hour) for the major components of the processing system. Trees from block A were processed in November 1986; trees from block B were processed in January 1987 (refer to table 5 for the production rates). On block A, loading the magnet chute presented a bottleneck to continuous processing of materials from the debarker through the shredder. At one time, all on-site loaders (4, including the one on the grapple-skidder) were being used to load the magnet chute and the shredder. At this time a formidable pile of woody debris had accumulated around the debarker. This debris pile caused delays and downtime for the debarker and idle time for the chipper.

Table 8—Operational-time components of the forwarder

Time component	Block A	Block B
	Percent	
Operational time:		
Productive time	75	57
Other work	2	21
Idle time	0	0
Delay time	15	6
Down time	8	16
Total	100	100

Table 9—Productive-time components of the forwarder

Time component	Block A	Block B
	Percent	
Productive time:		
Travel	44	57
Loading	53	40
Unloading	3	3
Total	100	100

Sorting—As the trees were delivered to the landing for processing by the forwarder, the mobile loader first set aside the saw logs and then separated the hogged-fuel material from the trees that could be processed into clean chips. This sorting process progressed rapidly, thereby allowing the loader to attend to its major role of feeding the debarker-delimber. Because the mobile loader handled all materials at least once, its production rate is based on the weight of all delivered products. Repeated handling of individual trees is not considered here. On block A, the production rate was 30 tons per productive hour for all functions performed by the mobile loader-sorter. The rate increased to 42 tons per productive hour on block B, where the material handling conveyor was in full operation.

During the observation periods, the percent of productive time spent in direct support of chips, saw logs, and hogged fuel was as follows: 74:15:12 and 78:12:10 on blocks A and B, respectively.

Clean-chip process—After clearing the incoming trees from the drop zone used by the forwarder, the loader moved into position next to the debarker-delimber to assist in the clean-chip operation. The loader would then typically feed one or two but sometimes as many as four trees into the debarker-delimber. As the cleaned stems emerged from the debarker-delimber, they were grabbed by the loading grapple attached to the chipper. The chipper operator continued to pull the trees through the chain-flail at a rate consistent with proper cleaning. The stems were then placed into the feed works of the chipper, which transformed the clean stems into clean chips and blew them into a waiting chip van. Bark content of less than 1 percent could easily be achieved with this method. The production rate of the chipper is the same as the production rate of the debarker in the clean-chip operation because both machines process the same trees and the rate is based on the weight of the chips in the van. Twice during the study, the debarker was bypassed and the chipper processed whole trees into hogged fuel. The chipper's production rate when producing hogged fuel was about 50 percent higher than its production rate for clean chips.

The production rate of the chipper was limited by the desired cleanliness of chips produced. The material feed rate of the chipper in linear feet per second was fixed because the feed rollers are geared directly to the chipping disc drive system. The chipper's production rate in tons per productive hour can only be increased by feeding larger trees or multiple trees (more basal area through the knives). When multiple trees are fed through the debarker, however, the effectiveness of the debarking chains is decreased, which results in higher bark content in the chips. Even though the debarker is designed to handle multiple stems, the typical load usually consisted of three or fewer trees during this study. This resulted in chips with a bark content of less than 2 percent, which was the goal of the operator.

From a block B sample observation of 504 loads of trees fed into the debarker-delimber, 87 percent of the loads were single trees, 11 percent were two trees at a time, and 2 percent were three or more trees.

Overall, the production rate of the chipper was 29 and 34 tons of pulp-quality chips per productive hour on blocks A and B, respectively.

Hogged-fuel process—The prototype shredder normally processed all materials that were not delivered as saw logs or clean chips into hogged fuel. Materials came from several sources: very small or unsound trees, repeatedly bucked by the chaser; limbs and trim ends from saw logs; limbs and broken tops discharged from the debarker-delimber; bark and fines discharged from the debarker-delimber; bark and other friable particles discharged by the chipper.

Observations on block B showed that an average of 70 loads per productive hour were dropped into the shredder hopper. Of these, 56 percent consisted of sawed stems and branches from the first and second categories above.

A conveyor belt lifted bark and limbs out of the debarker-delimber and discharged them onto another system[5] of two conveyors that continuously separated the materials into three categories. Larger limbs usually overshot the second conveyor and were side cast directly in front of the conveyor that discharged materials from the debarker-delimber. Fine materials, including most of the bark, filtered down through openings in the top bed of the second conveyor and were delivered to a third conveyor along with any metal chain pieces that occasionally became separated during operation. Branches that did not filter down through the top bed of the second conveyor were piled within easy reach of the shredder loading grapple. The third conveyor then lifted the fine materials and any possible chain particles to a chute that passed over a 1000-pound permanent magnet. The magnet was designed to trap chain particles to prevent damage to the sharp knives of the shredder. Fine wood particles that passed over the magnet were collected in a hopper that was regularly emptied by the shredder loading grapple, alternately with branches and other debris as listed above. The shredded hogged fuel was then blown into a waiting van.

[5] The second and third conveyors were used on block B but not on block A. The added material-handling equipment improved production efficiency. Moreover, large quantities of materials did not accumulate during the day on block B. On block A, all three loaders were typically used at the end of each workday to load the shredder until the landing was cleaned.

The shredder operator opened the clam-shell doors of the hopper over the shredding drum each time a load was dropped in by the grapple. The doors can be seen in figure 9. Materials from the conveyor system and the saw-log operation were small enough to easily fit into the shredder hopper. The small trees, however, had to be progressively bucked by a chaser with a chain saw to make hopper-length loads (4 to 5 feet long) for the grapple to drop into the hopper. This repeated bucking operation progressed faster than might have been expected because the shredder operator used the loading grapple to move the trees incrementally, in bunches, over a crosswise cull log. This enabled the chaser to buck many trees at a time without moving wood or binding the saw. The result was a clean landing with almost all woody materials being hauled out in a van or on a log truck.

The production rate of the hogged-fuel process was calculated based on the weight of hogged fuel leaving the site. The primary machine in the hogged-fuel process was the shredder, which handled all the hogged-fuel materials. The production rate of the shredder was 10 tons per hour on block A and 10.5 tons per hour on block B.

Even though materials destined for hogged fuel were also handled repeatedly by the sorter-loader and partially by the debarker-delimber, the chipper, the conveyor-magnet system, and the chaser, the hogged-fuel production rate was attributed to the shredder because of its singular function. The other systems contributed to the production rate but were not specifically characterized by the amount of their contribution relative to the contribution of the shredder or to the other products they handled. The interrelated functions of the processing equipment make simple assignments of costs equally difficult and arbitrary. No production rate was calculated for the conveyor system, though it clearly processed only hogged-fuel materials.

When the chipper was used without the debarker to produce hogged fuel, larger cross-sectional areas of trees (multiple stems) were fed into the chipper, increasing its effective production rate, without concern about bark content. One van on block A was filled with 47,600 pounds of hogged fuel in 27 minutes, a hogged-fuel production rate of 52.9 green tons per productive hour for the chipper.

Equipment Availability

The results of equipment availability (or reliability) are presented in table 10. The study period was an extremely short time sample for predicting long-term reliability. The observed availabilities are useful for those wishing to accumulate these data with other reported data. All machines experienced relatively high availability, especially considering the minor amount of prior operating time on the three new prototype machines.

Table 10—Equipment-availability and productive-time ratios from doghair harvesting and processing study

Machine	Equipment availability		Productive-time ratio	
	Block A	Block B	Block A	Block B
	Percent			
Harvesting equipment:				
Feller-buncher	95	99	91	99
Forwarder	92	84	75	57
Processing equipment:				
Sorter-loader	98	100	93	86
Debarker-delimber	88	84	55	61
Chipper	90	93	58	60
Shredder	86	99	80	86

The availability was higher on block B than on block A for every piece of equipment except the forwarder and the debarker-delimber. The forwarder suffered two hydraulic hose failures on block B, and the debarker-delimber was down for over 3 hours on block B with an immobile discharge conveyor. The availability of the shredder was significantly improved on block B. The discharge chute became clogged two times on block A because too much wet material (in the form of old cull logs) was dumped into the hopper at one time. This did not happen on block B, where wet materials were loaded alternately with the other materials. The additional conveyors helped smooth out delivery of fine materials to the shredder, and they separated limbs and fines, giving the shredder operator a selection of materials to load. Because of the material sorting action of the conveyor system, the magnet chute also rarely became clogged on block B.

Productive-Time Ratio

The ratios of productive time are also reported in table 10. These ratios were used for calculating costs and production rates on the common basis of productive hours. The ratios may also be used by planners to estimate scheduled hours required to complete a future job.

The feller-buncher worked independently with high availability at a single task. Consequently, the productive-time ratio of the **feller-buncher** was consistently high.

The **forwarder** had production capacity to spare; therefore, the operator used some idle time to perform other useful work, such as skid road maintenance. This resulted in a relatively low productive-time ratio in spite of high availability.

Although the availability of the **loader** was 100 percent on block B, the loader had a lower productive-time ratio there than on block A. This is a result of the loader being delayed while the belt of the debarker-delimber was jammed.

Because of the disabling belt jam-up, described earlier, the **debarker-delimber** lost productive time on block B. The results showed, however, an overall rise in productive-time ratio for the debarker on block B. This indicates the overall improvement in system availability on block B, which had the benefit of two additional conveyors to move woody debris (principally limbs and bark) continuously from the debarker across the magnet chute for the shredder.

The jammed debarker left the **chipper** idle because it could not operate while the debarker was being serviced. Consequently, the productive-time ratio of the chipper was lower on block B than on block A. The chipper and the shredder were delayed for a few minutes every time a van was filled and an empty van was moved into position.

The productive-time ratios for the chipper include the times when the chipper was used to produce hogged fuel instead of clean chips. The operator chose to do this on occasion to meet his hogged-fuel market demand, while balancing the flow of materials arriving at the in-woods processing site.

The debarker was purposely idled for the time when the chipper was producing hogged fuel. On one occasion on block B, the chipper filled a van with hogged fuel in 36 minutes. The debarker was not needed for this operation. The debarker was out of production for a total of 2 hours and 22 minutes on that occasion to support this use of the chipper to produce hogged fuel: 37 minutes to reconfigure the debarker (remove its top) to bypass whole trees, 36 minutes to produce the load of hogged fuel, 32 minutes to restore the normal configuration, and another 37 minutes of related delay before the debarker was restarted. Still, the productive-time ratio for the debarker-delimber was higher on block B.

The productive time ratio of the **shredder** was higher on block B, primarily because the shredder-feedstock handling system was improved by the added conveyors.

Costs

Machine rates were calculated for each piece of harvesting and processing equipment. The calculations include ownership and operation costs. They do not include costs associated with equipment move-in, set-up, overnight maintenance, or road and landing construction; company risk and profit are also excluded. Costs for the conveyor-magnet system[6] were included, but they accounted for only about $0.06 per ton of total product. No interest payments are included for the shredder and the debarker-delimber because funds for these machines were provided from external sources. Average yearly investment values were included, however. Machine rates, broken down by ownership and operating costs (with the exclusions noted above), are shown in table 11.

The productive costs of harvesting and processing are shown in table 12. These costs were calculated by combining the production results of table 5 with the cost results of table 11. The total productive cost was $9.52 and $7.80 per ton on blocks A and B, respectively.

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[6] Conveyors of this type cost about $20,000. They have negligible operating costs because they are all powered by excess hydraulic power from other machinery, and no additional operator is required.

Table 11—Costs and machine rates for equipment used for harvesting and in-woods processing of small-diameter trees

Machine	Block A Own cost	Block A Operate cost	Block A Machine rate	Block B Own cost	Block B Operate cost	Block B Machine rate
	Dollars per productive hour					
Harvesting equipment:						
Feller-buncher	46.86	26.05	72.91	43.07	24.35	67.42
Forwarder	35.71	29.58	65.29	46.98	37.66	84.64
Processing equipment:						
Sorter-loader	30.83	25.41	56.24	33.34	27.09	60.43
Debarker-delimber	15.04	2.10	17.14	13.56	2.10	15.66
Chipper	35.74	44.98	84.79	43.48	38.71	82.19
Shredder	44.51	32.06	76.57	41.41	30.38	71.79
Magnet-conveyor	.32	0	.32	2.21	0	2.21

Table 12—Productive costs per green ton for equipment used for harvesting and in-woods processing of small-diameter trees

Machine	Block A	Block B	Materials
	$/Ton[a]		
Harvesting equipment:			
Feller-buncher	1.33	1.13	Whole trees
Forwarder	1.42	1.30	Whole trees
Total	2.75	2.43	
Processing equipment:			
Sorter-loader	1.87	1.44	Mixed
Debarker-delimber	.59	.46	Whole trees
Chipper	2.92	2.42	Clean stems
Shredder	7.66	6.84	Mixed
Magnet-conveyor	.04	.23	Bark and fines
Total[b]	6.77	5.37	
Total system cost[b]	9.52	7.80	

[a] Each entry is based on the green tons of material processed by a particular machine (for example: whole trees, clean stems, etc.).
[b] The itemized productive costs of each component of the processing system are not additive because each machine processes only a portion of the total product output. Processing costs were calculated by summing the products of the cost per ton and the respective tonnage processed by each machine and then dividing that sum by the total weight of delivered products.

The productive costs incurred to process each product (such as, the clean-chip operation) are difficult to calculate without arbitrary assignment of the costs of the multiple-purpose machines that operate as an integrated system for the good of the entire system. Therefore, productive costs of each machine are given (table 12), based on the weight of material handled by each machine. Productive costs of the total system based on prorated use of each machine for its respective proportion of products handled are also shown in table 12. Because the different pieces of equipment process different weights of material, and because some materials may be handled by more than one piece of equipment, the productive costs are not truly additive. These costs should be considered along with the percentage breakdown of the products produced (table 3). It would be incorrect to focus on only one product and attempt to isolate the unit cost of that product only. At the study site, all products are delivered by the system. Without all products being delivered, a harvest may not be feasible because of economics, environmental impacts, or other reasons discussed previously. There could be no clean chips without the debarker; no hogged fuel without the collective inputs of materials from the sorting, saw log, and chipping operations; and no saw logs from these stands without a way to clean the harvest site and market the other products.

Conclusions

The steep-slope feller-buncher and clam-bunk-skidder harvesting system was well adapted to the stand and terrain conditions of this study. The feller-buncher functioned remarkably well, with lift capacity, power, and gradability to spare. The clam-bunk skidder kept pace with the felling and the processing production rates, with extra time to do other tasks such as skid road maintenance. Productive costs for harvesting the study blocks were $2.75 and $2.43 per ton on blocks A and B, respectively.

The in-woods, multiple-product processing system demonstrated a consistent ability to sort and process the small-diameter trees into a marketable mix of products. All machines had high reliability and high productive-time ratios. Average daily production was about three truck loads of logs, eight van loads of clean chips, and four vans of hogged fuel. Productive costs for processing the material from study blocks A and B were $6.77 and $5.37 per ton, respectively.

The mobile sorter-loader and the chipper appeared to be sized adequately for this application. These are regular, production-line equipment items, and their reliabilities were very high even though the chipper had very little operating time on it before this study started. The multi-stem debarker-delimber, the shredder, and the magnet-conveyor system were designed, fabricated, and used for the first time on this job; all worked well. Occasional system clogs were encountered, especially with large, unsound cull logs (shredder) or extremely dense crowns (debarker). These clogs were all overcome quickly, and the system operated nearly continuously. The added conveyors on block B enhanced the material-handling capabilities within the processing system.

The chipping operation could not proceed without the mobile loader because the loader was needed to insert trees into the debarker; chips were not produced while the loader tended to log trucks, for example, but log trucks were usually loaded during other slack times for the chipper, such as during knife or van changes. The interruptions were minimal, and an additional loader is probably not warranted.

The total system-productive costs for harvesting and processing multiple products from the two study blocks in the doghair stand were $9.52 per ton in block A and $7.80 per ton in block B. The weight ratio of chips to total product weight was 53 percent on both blocks. Saw logs comprised 16 percent of the product weight on block A and 21 percent on block B. The remaining product was hogged fuel: 31 and 26 percent on blocks A and B, respectively. The actual mix of delivered products should be considered simultaneously with the total system-production costs because it is not reasonable to isolate the cost of producing individual products in an integrated system such as this. The important questions to answer are as follows: Is the system profitable? Would a different configuration be more profitable in this market? Would this or a different configuration be more profitable in a different market?

The relatively low productive costs of this system, coupled with short haul, local markets for all three products, and a continuing need for operations in similar stands, combine to make the system feasible. The substantial capitalization costs, however, can be justified only with adequate forest inventories and thorough planning.

This system or adaptations of it may be technically and economically suited to harvest and process other stands of small-diameter trees, where total marketing is required to justify any harvest, and where it is desirable to collect the energy-wood component of the stand.

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Metric Equivalents

1 inch = 2.54 centimeters
1 foot = 30.48 centimeters
1 mile = 1.609 kilometers
1 acre = 0.405 hectare
1 cubic foot = 0.0283 cubic meter (stere)
1 pound = 0.454 kilogram
1 ton = 0.907 metric tonne
1 gallon = 3.785 liters

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Appendix

Ownership Cost Information

The parameters used for calculating ownership costs are summarized in table 13 for the harvesting machines on both study blocks. Table 14 provides the ownership-cost summary for the sorter-loader and the debarker-delimber. Table 15 shows the ownership-cost summary for the chipper and the shredder.

Table 13—Equipment-ownership costs for the feller-buncher and the forwarder

		Feller-buncher		Forwarder	
Parameter	Units	Block A	Block B	Block A	Block B
Original investment	$	328,000[a]	328,000[a]	206,000	206,000
Depreciation period	Yrs	5	5	5	5
Annual utilization	S-hrs/yr	2,000	2,000	2,000	2,000
Machine availability	%	95	99	92	84
Productive-time ratio	%	91	99	75	57
Salvage value	%	10	10	10	10
Salvage value	$	32,800	32,800	20,600	20,600
Annual depreciation	$/yr	59,040	59,040	37,080	37,080
Average yearly investment	$/yr	209,920	209,920	131,840	131,840
Interest rate	%	10.75	10.75	10.50	10.50
Annual interest	$/yr	22,566	22,566	13,843	13,843
Taxes, license, and insurance	$/yr	3,674	3,674	2,637	2,637

See footnote on following page.

Table 13—continued

Parameter	Units	Feller-buncher		Forwarder	
		Block A	Block B	Block A	Block B
Scheduled hours	S-hrs/job	17.25	17.3	25.1	27.6
Fixed costs	$/job	735.66	737.67	698.96	672.18
Fixed costs per scheduled hour	$/S-hr	42.64	42.64	26.78	26.78
Fixed costs per productive hour	$/P-hr	46.86	43.07	35.71	46.98

[a] Estimated capital cost; not a market-derived value.

Table 14—Equipment-ownership costs for the sorter-loader and the debarker-delimber

Parameter	Units	Sorter-loader		Debarker-delimber	
		Block A	Block B	Block A	Block B
Original investment	$	230,000	230,000	85,000[a]	85,000[a]
Depreciation period	Yrs	5	5	5	5
Annual utilization	S-hrs/yr	2,000	2,000	2,000	2,000
Machine availability	%	98	100	88	84
Productive-time ratio	%	93	86	55	61
Salvage value	$	20,000	20,000	5,000	5,000
Annual depreciation	$/yr	42,000	42,000	16,000	16,000
Average yearly investment	$/yr	146,000	146,000	53,000	53,000
Interest rate	%	9.00	9.00	0	0
Annual interest	$/yr	13,140	13,140	0	0
Taxes, license, and insurance	$/yr	2,190	2,190	530	530
Scheduled hours	S-hrs/job	30.95	28.0	28.5	26.4
Fixed costs	$/job	887.34	802.76	235.70	218.33
Fixed costs per scheduled hour	$/s-hr	28.67	28.67	8.27	8.27
Fixed costs per productive hour	$/p-hr	30.83	33.34	15.04	13.56

[a] Estimated capital cost; not a market-derived value.

Operating Cost Information

The parameters used for the calculation of operating costs are summarized in Table 16 for the harvesting machines on both study blocks. Table 17 provides the cost summary for the sorter-loader and the debarker-delimber, and Table 18 gives the operating-cost summary for the chipper and the shredder.

Table 15—Equipment-ownership costs for the chipper and the shredder

		Chipper		Shredder	
Parameter	Units	Block A	Block B	Block A	Block B
Original investment	$	203,000	203,000	350,000[a]	350,000[a]
Depreciation period	Yrs	5	5	5	5
Annual utilization	S-hrs/yr	2,000	2,000	2,000	2,000
Machine availability	%	90	93	86	89
Productive-time ratio	%	58	60	80	86
Salvage value	$	20,000	20,000	10,000	10,000
Annual depreciation	$/yr	36,600	36,600	68,000	68,000
Average yearly investment	$/yr	129,800	129,800	214,000	214,000
Interest rate	%	10.50	10.50	0	0
Annual interest	$/yr	13,629	13,629	0	0
Taxes, license, and insurance	$/yr	1,947	1,947	3,210	3,210
Scheduled hours	S-hrs/job	29.97	27.60	30.86	29.40
Fixed costs	$/job	781.92	720.08	1,098.92	1,046.93
Fixed costs per scheduled hour	$/s-hr	26.09	26.09	35.61	35.61
Fixed costs per productive hour	$/p-hr	44.98	43.48	44.51	41.41

[a] Estimated capital cost; not a market-derived value.

Table 16—Equipment-operating costs for the feller-buncher and the forwarder

		Feller-buncher		Forwarder	
Parameter	Units	Block A	Block B	Block A	Block B
Total crew wage	$/hr	11.50	11.50	11.50	11.50
Supervision	% of wages	67	67	67	67
Fuel cost	$/gal	0.61	0.61	0.61	0.61
Fuel consumption	Gal/p-hr	6.5	6.5	5	5
Hourly fuel cost	$/p-hr	3.96	3.96	3.05	3.05
Hourly oil cost	$/p-hr	.99	.99	.92	.92
Hourly labor costs	$/p-hr	21.10	19.40	25.61	33.69
Hourly fuel and oil costs	$/p-hr	4.95	4.95	3.97	3.97
Hourly operating cost	$/p-hr	26.05	24.35	29.58	34.66
Machine rate	$/p-hr	72.91	67.42	65.29	84.64

Table 17—Equipment-operating costs for the sorter-loader and the debarker-delimber

Parameter	Units	Sorter-loader		Debarker-delimber	
		Block A	Block B	Block A	Block B
Total crew wage	$/hr	11.50	11.50	0	0
Supervision	% of wages	67	67	67	67
Fuel cost	$/gal	.61	.61	.61	.61
Fuel consumption	Gal/p-hr	6	6	3	3
Hourly fuel cost	$/p-hr	3.66	3.66	1.83	1.83
Hourly oil cost	$/p-hr	1.10	1.10	.27	.27
Hourly labor costs	$/p-hr	20.65	22.33	0	0
Hourly fuel and oil costs	$/p-hr	4.76	4.76	2.10	2.10
Hourly operating cost	$/p-hr	25.41	27.09	2.10	2.10
Machine rate	$/p-hr	56.24	60.43	17.14	15.66

Table 18—Equipment-operating costs for the chipper and the shredder

Parameter	Units	Chipper		Shredder	
		Block A	Block B	Block A	Block B
Total crew wage	$/hr	11.50	11.50	11.50	11.50
Supervision	% of wages	67	67	67	67
Fuel cost	$/gal	.61	.61	.61	.61
Fuel consumption	Gal/p-hr	9	9	11	11
Hourly fuel cost	$/p-hr	5.49	5.49	6.71	6.71
Hourly oil cost	$/p-hr	1.21	1.21	1.34	1.34
Hourly labor costs	$/p-hr	33.11	32.01	24.01	22.33
Hourly fuel and oil costs	$/p-hr	6.70	6.70	8.05	8.05
Hourly operating cost	$/p-hr	39.81	38.71	32.06	30.38
Machine rate	$/p-hr	84.79	82.19	76.57	71.79

Glossary

Chipper—A machine with sharp knives used for processing entire stems into pulp chips.

Doghair—A term used in this report to describe dense stands of small-diameter trees that are overstocked and growing very slowly.

Feller-buncher—A machine used for severing trees from their stumps and arranging the severed stems into piles.

Forwarder—See skidder. The operator generally referred to his skidder as a forwarder because of the function it performed. Consequently, the terms are used interchangeably in this report, although a forwarder usually transports trees or tree segments without dragging any part of the tree.

Friable—Easily crumbled or pulverized.

Hogged fuel—Woody biomass that has been processed by a hammer hog, shredder, or similar comminution device so that it may be easily handled in bulk and burned for conversion into heat energy (also called hog fuel); usually comprised of low value or very small-diameter trees, cull logs, branches, and tree tops.

Landing—A processing site usually adjacent to both the harvesting area and a surfaced roadway, accessible by both highway transport vehicles and forwarding equipment.

Loader—A machine used for lifting and moving trees and tree parts.

Machine rate—Hourly cost of owning and operating a piece of equipment.

Productive cost—Cost of owning a piece of equipment per unit of production in units of dollars per ton.

Shredder—A drum-type chipper built by Hermann Brothers for processing limbs, bark, small trees, and other woody biomass into hogged fuel.

Skidder—A ground-based machine that transports trees and tree parts from the stump to the landing.

Supervision rate—A fraction of the total crew wages that is charged to basic supervision of labor and overhead, expressed as a decimal number, where 1.0 means 100 percent of wages. This rate includes unemployment insurance and other employee overhead expenses.

Time:

Scheduled: Total work time when the equipment was allocated for operation on the study blocks. Scheduled time for all jobs during a year would total the annual-use hours for the equipment.

Operating: The inclusive time between the first moment of productive time until the machine shuts down for the day. Operating time includes all productive time, idle time, delay time, other work performed, and all downtime (planned and unplanned) during the operating day(s). For this study, warm-up and cool-down times and normal after-hour fueling and maintenance times were not included in operating time. Operating time was recorded by an observer, unlike scheduled time which was established (allocated) before the operation began.

Productive: Scheduled time less all unproductive time segments, such as idle, delay, and down times.

Idle: Periods of time when equipment could not process material because no material was available from the previous process. (No workload.)

Delay: Periods of time when equipment could not complete material processing because the subsequent process was fully loaded and could not accept new material (bottleneck ahead).

Down: Periods of time when equipment was unavailable for productive work because of scheduled or nonscheduled interruption of processing owing to mechanical or operator inability to proceed.

Turn—A complete work cycle, referring to a specific tree-harvesting process, such as (1) cutting a tree and positioning it on the ground or (2) loading felled trees and transporting them to a landing.

Forwarding—The process of moving trees and trees parts from the stump to a landing.

Lambert, Michael B; Howard, James O. 1990. Cost and productivity of technology for harvesting and in-woods processing small-diameter trees. Res. Pap. PNW-RP-430. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 37 p.

A study was conducted on the productivity and cost of an integrated harvesting and processing system operating in small-diameter timber (western hemlock-type) on the Olympic Peninsula of western Washington. The system uses a new steep-slope feller-buncher, a clam-bunk grapple-skidder (forwarder), a prototype chain-flail debarker-delimber, a chipper, a conveyor system, and a prototype shredder. The study showed that the system harvested and processed trees at a combined-system cost of $7.80 per green ton at a production rate of 455 green tons per day. The delivered product mix was 53 percent chips, 21 percent saw logs, and 26 percent hogged fuel by weight. The productivity and machine rate of each piece of harvesting and processing equipment and other data are given.

Keywords: Logging, whole-tree harvesting, feller-buncher, intensive harvesting, utilization, integrated harvesting, in-woods chipping, small-tree harvesting.

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