AN ABSTRACT OF THE THESIS OF

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Many high-elevation stands of noble fir in the northern Oregon Cascades are being actively managed. Forest managers are investigating different activities that will control stand impacts and the subsequent spread of *Heterobasidion annosum* a rot pathogen on the Warm Springs Indian Reservation. The purpose of this study was to quantify the relationship of logging production and costs with associated residual stand damage during a commercial thinning operation. Investigated in the study were four ground-based harvesting systems and two different harvest unit layout methods.

The harvest systems encompassed a variety of equipment and mechanization levels ranging from mechanized felling and bunching with grapple skidders to manual felling, limbing, and bucking using a rubber-tired skidder equipped with a winch line. In addition, each harvest system was compared using two layout methods. The first method was conventional or logger's choice and the second was a designated method incorporating proven methods for reducing stand damage. Log lengths varied from whole-tree to log-length depending on the harvest system employed. Logging production and costs were determined for the harvesting systems using a combination of detailed and shift level time studies. A stand damage survey conducted simultaneously with production studies determined percent residual stand damage, specific equipment causing damage, and individual scar characteristics.

Harvesting costs for the four different systems and layout methods ranged from \$67.77/MBF-\$92.68/MBF, with residual stand damage of 20.12-62.62%. Equipment

size, log lengths, and layout method were found to affect total residual stand damage. Reducing the use of larger, more mechanized pieces of equipment in the stand and keeping log length to a minimum resulted in a significant decrease in residual stand damage. Cost differences between designated and conventional layout methods for each harvest system were minimal. The main difference in harvesting cost was between the different systems and log lengths. Harvesting costs varied, being similar for the highest and lowest mechanized systems but increasing with the intermediate harvesting systems.

Harvest System Selection and Design for Damage Reduction in Noble Fir Stands
(A Case Study on the Warm Springs Indian Reservation)

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APPROVED:

Major Professor, representing Forest Engineering

Chair of Department of Forest Engineering

Dean of Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Peter J. Matzka, Author

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Harvest System Selection and Design for Damage Reduction in Noble Fir Stands
(A Case Study on the Warm Springs Indian Reservation)

1.0 INTRODUCTION

Harvest system selection and timber sale planning are important factors in the effort to minimize residual stand damage. The type of harvest system used in commercial thinning has been shown to influence the amount of damage to residual trees (Aho et al. 1983a, 1983b; Filip and Schmitt 1990). In addition, even though residual stand damage occurs during harvesting, the amount can be reduced through timber sale planning (Aho et al. 1983a, 1983b).

The reduction and prevention of stand damage in noble fir (*Abies procera*) is of special interest to the Warm Springs Indian Reservation (WSIR). In the northern zone of the reservation, at higher elevations, there are mixed stands of noble fir and Douglas-fir (*Pseudotsuga menziesii*). These high-elevation ridge tops are relatively flat (0-25% slopes), which makes the use of ground-based logging possible. In these stands, any management activity increases the potential for damage to the residual trees and subsequently, an increase in disease. Specifically, annosus root disease, caused by the fungus *Heterobasidion annosum*, can enter a tree through a stem or root wound (Aho et al. 1983b).

This project was the final step in a larger, three-phase, long-term study on the WSIR, conducted by Oregon State University (OSU) in cooperation with WSIR and the Bureau of Indian Affairs (BIA). Phase I investigated the effects of annosus by measuring decay and spread within standing trees of managed and unmanaged stands (Sullivan 1997). Phase II predicted the growth and future yield of noble fir-dominated stands. A growth model was used to compare future tree volume and grade in managed and unmanaged stands (Stinson 1997). The focus of Phase III's research in noble fir thinning was to determine production rates for alternative harvesting systems, residual stand damage associated with harvesting, and layout costs and stand damage associated with alternative layout methods.

The desired outcome of Phase III was to understand and quantify the relationship of logging production and costs with associated residual stand damage during a commercial thinning operation. Included in this relationship were the damage associated with alternative layout methods. The harvesting systems investigated were:

A. Feller-buncher → Grapple skidder → Delimber

B. Manual felling → Shovel, prebunching → Grapple skidder→ Delimber

C. Manual felling, limbing, bucking → Shovel, prebunching → Grapple skidder

D. Manual felling, limbing, bucking → Rubber-tired skidder with winch line

Reducing stand damage does not bring an immediate economic benefit. The high value of large noble fir logs on the export market is the incentive for managing these stands. Future returns from harvesting can be increased if the incidence of disease and rot is reduced. With the combined results of all three phases, a cost cause-and-effect relationship can be investigated for the noble fir stands. From the decay model (Phase I), growth and yield model (Phase II), and the production and damage model (Phase III), a comprehensive analysis can link all three components.

Information on production rates and stand damage is an important tool for forest managers. By knowing the specific production costs associated with alternative harvesting systems better management practices and objectives can be met. In addition, all the systems investigated are feasible and well within the practical approaches to harvesting these stands. The unit planning and layout methods that were tested can work in conjunction with present harvesting systems as well as those described in this study.

2.0 LITERATURE REVIEW

Much work on skidding production associated with commercial thinning and the damage incurred during harvesting operations commonly has compared different logging systems. However, most of these studies were conducted in younger stands of smaller trees with an average dbh (diameter at breast height, 4.5 ft) of 10-12 in. (Aho et al. 1983a, 1983b; Tesch and Lysne 1983; Clements et al. 1995). The WSIR project was specifically aimed at the use of ground based logging systems that reduce damage in 70 to 100-year-old stands. Furthermore, the production of these systems needed to be addressed alongside stand damage. This literature review addresses the following production and stand damage issues: equipment selection, harvest preparation, and sale administration. In addition, an approach for determining stand damage is discussed.

2.1 Equipment Selection

Matching the appropriate size and type of logging equipment to topography and tree size is important in equipment selection (Aho et al. 1983b). With the variety and possible combinations of equipment, selection can be difficult. To minimize stand damage during logging, Aho et al. (1983b) suggests the following:

- Restrict size and type of logging equipment.
- Match logging system to the topography.
- Match size of logging equipment to size of material being removed, spacing of crop trees, and skid trail width.

Other suggestions included using systems (equipped with winches) that confine equipment to the skid trails and pull winch lines to the logs. A rubber-tired skidder or tractor can employ can be used to reduce the risk of machines wounding residual trees (Garland 1983).

In the Blue Mountains of northeast Oregon, Clements et al. (1995) studied stand damage during a commercial thinning with four ground-based harvesting methods. These methods were:

- Conventional harvesting with a chainsaw and rubber-tired skidder.
- Mechanized harvesting with a feller-buncher, rubber-tired skidder, and delimber.
- Mechanized harvesting with a single-grip harvester and rubber-tired skidder.
- Combination of multifaceted mechanized harvesting approaches involving a chainsaw, feller-buncher, single-grip harvester, and rubber-tired skidder.

Preliminary conclusions are listed below:

- A conventional harvesting system consisting of manual felling and grapple-skidding resulted in the least amount and severity of wounding across diverse site conditions.
- When mechanized harvesting was involved (either feller-buncher or single-grip), the degree of wounding increased significantly.
- Multifaceted mechanized systems incurred the highest level of wounding.
- Stand and terrain conditions and operator experience may have partly explained the increased wounding with mechanized systems over traditional systems.

The four systems were compared and duplicated on two study sites. The conventional system caused overall damage of 11 and 18%. The mechanized system produced 21 and 16% damage, the harvester showed 35 and 30%, while the combination systems produced 46 and 14% damage. No production data were reported for any harvest system.

Bradshaw (1979) conducted a study in a partial cut to compare the productivity of two skidding systems. These systems were designated skid trails and winching versus conventional harvesting with non-designated skid trails. A large average DBH of 22 in. (in a mixed stand) produced an average daily production of 44 MBF (thousand board feet), at 2.28 MBF per cycle. The average skidding and winching distances per cycle were 515 and 57 ft, respectively, which produced 3.8 logs per turn. A Caterpillar D-7F removed an average of 10-12 MBF per acre. This concluded that:

- Winching and designated skid trails cost 29% more than conventional logging.
- Production rates were 11% less with winching and designated skid trails
- Preset chokers could increase productivity and decrease the cost of winching.

In a similar study Bennett (1993) investigated a slightly older thinning operation on a 60 to65-year-old Douglas-fir stand in coastal British Columbia. Designated skid roads were 13-ft wide and spaced 330-ft apart. This network of trails had an average skid distance of 295 ft and a 65-ft winching distance. The crawler-tractor was allowed to travel off the designated skid trails. Bennett concluded, "The light weight, the narrow track gauge, and the maneuverability of the small crawler-tractor were essential to the success of the dispersed skidding operation. Proficiency in the felling phase is critical to the success of the partial cutting methods. Accurate directional felling is needed to place the timber in the lead for efficient skidding while preventing damage to the residual trees".

Little is known about stand damage caused by feller-bunchers and shovel-bunching in a fir-dominated commercial thinning operation. Although there has been much work done in younger pine plantations 15 to 25 years old, older, larger stands have not been investigated. A study in New Zealand compared bunching of logs by a Bell Logger with the use of grapple skidders for extraction (Ashby and Vaughan 1988). In a partial cut using the Bell Logger for bunching, a 15-year-old pine plantation was logged by two felling techniques, and a mechanized system (Lako 3T harvester, feller-buncher) and manual chainsaw felling. The comparison showed little difference in the bunching time with the Bell Logger. The mechanized system was slightly faster due to the partial bunching of the feller-buncher. Logs were skidded to a central landing using a grapple skidder.

2.2 Harvest Preparation

The best way to reduce decay losses associated with thinning wounds is to avoid injuring residual trees. Aho et al. (1983a, 1983b) suggested the following to reduce the amount of residual stand damage prior to harvesting:

- Restrict logging seasons. Do not allow logging during the spring and early summer when sap is flowing and bark is loose because wounding is more likely and injuries are often larger.
- Mark the residual trees to make them easier to see and avoid damaging during logging.
- Lay out skid roads in advance. This is one of the best ways to reduce logging damage. Skid trails should be cleared wider than the skidding vehicle, but no less than about 8-ft wide.
- Use straight-line skid trail patterns, and avoid sharp turns. Straight skid trails minimize skidding distance.
- When possible, leave cull logs and buffer ("bump") trees along the edges of skid trails. Remove "bump" trees during the last turn.
- Limit log length according to the spacing of residual trees. Skidding long logs or the entire bole increases the probability of damaging residual trees

Aho et al. (1983b) studied, ground-based logging systems and compared conventional layout methods and to those designed to reduce stand damage. The production rates for these systems, however, were not reported. The damage to residual trees on four conventionally logged units was 22% and 33% (rubber-tired skidder in two logged areas), 35% (steel-track tractor), and 50% (grapple skidder). Procedures designed to minimized injury to residual trees resulted in damage reductions to 5% (rubber-tired skidding), 11% each (steel-track tractor in two logged areas), and 14% (steel-tractor in a third area).

Smith (1986) reinforced the suggestions by Aho et al. (1983a, 1983b), and proposed several harvest planning techniques (Smith, 1986):

- Trees should be extracted in a straight line. If trees must be pulled around curves, leave trees can act as buffers for residual trees. Leave trees would be removed as the final step in the operation.
- Better results can be achieved by closely following rules for cutting or by marking demonstration small plots for desired cutting.
- Mark the residual trees in the stand. Even though these trees are more numerous and take longer to mark, they become more visible to the cutters.

Froehlich et al. (1981) studies the productivity of conventional logging and logging with designated skid roads. They wanted to determine the reduction in area impacted by designated skid roads when both systems used winch lines. In young Douglas-fir stands with ground slopes up to 30%, several conclusions where found:

- Skid trails in the conventional layout by loggers consumed 20% of the harvest area.
- When designated skid trails were used, however, they comprised only 11% of the harvest area at a 100-ft trail-spacing, and 7% and 4% of the area, respectively, at 150 and 250-ft spacings.
- Winch line pull distances for conventional logging were 32.8 ft, whereas areas with 100 to 150-ft spacing required an average winch distance of 34 ft.
- Overall productivity of logs per hour was similar for both conventional and designated skid road systems.

The use of designated skid trails and tree-length logging was beneficial compared to the traditional method of non-designated skid trails and tree-length logging (Olsen and Seifert 1984). The use of designated skid trails, however, increased the cost on three of the four systems when whole-tree logging was employed (based on a hypothetical comparison using regression models).

The "bump" tree suggested by Aho et al. (1983a, 1983b) can be used along with corrugated pipe ("tree bandage"). To prevent scarring, sections of corrugated polyethylene culvert pipe were split longitudinally and placed around the key rub trees that bordered skidding routes (Bennett 1993). This prevented excessive damage to rub trees, and could be used on residual trees if necessary. The installation of such a barrier takes less than a minute to place on a tree and the corrugated pipe can be carried easily on the back of a skidder or Cat.

2.3 Sale Administration

Once a logging operation proceeds, it is important to gain the cooperation of the loggers. Aho et al. (1983a, 1983b) suggests taking the following actions during the logging operations:

- Communicate desired results to the contractor through training and supervision. Convince operators that damage to residual trees is unnecessary and will not be tolerated.
- Fell and skid trees on skid roads before cutting other timber; otherwise, fellers have trouble finding the skid trails and felling the timber to lead. Cut stumps in skid trails as low as possible, 3 to 4 in., to prevent the skidder from being shunted into residual trees.
- Use directional felling. Trees should be felled about 45 degrees towards or away from skid trails to reduce skidder maneuvering and load pivoting.

- Limb, top, and buck trees before skidding. Limb flush to the bole.
- Do not thin too heavily stands of young trees or thin-barked species such as true firs and hemlocks. This can result in release shock or sun scald.

Many difficulties can be avoided if both timber markers and loggers plan for the felling and removal of trees. It takes cooperation and understanding between land managers and loggers to minimize residual stand damage. Smith (1986) proposed several factors for a sale administrator to consider in controlling damage:

- There must be adequate incentives for loggers.
- The cheapest-possible logging is inevitably poor logging, and ultimately invites regulation and restrictions.
- Almost any kind of logging system can be successful if supervisors make it clear that good work is expected.
- All parties must be involved in the planning and decisions-making of an operation.

2.4 Determining Stand Damage

A study conducted by Han and Kellogg (1997) evaluated five different methods for determining stand damage in the Oregon Coast Range. These included:

- 100% survey
- Systematic circular plots
- Systematic transects
- Transects along yarding roads
- Random circular plots

The 100% survey was used as the benchmark for determining the accuracy and efficiency of the other four methods. These were tested and contrasted to identify the best method for an overall survey of stand damage. Systematic circular plots were most efficient, but overall accuracy varied only slightly among all.

3.0 OBJECTIVES

The broad objective of this study was to determine the production rates of four harvesting systems in noble fir stands being commercially thinned on the WSIR. In addition, residual stand damage associated with the four harvesting systems was determined when two different layout prescriptions were used. The layout prescriptions were the conventional method and a "designated method" designed to reduce stand damage. With this information a relationship could be determined between logging cost and stand damage. The specific objectives to accomplish this overall goal were:

3.1 Determine production rates and cost per unit volume for four harvesting systems (refer to system description and specification, section 5.1).

3.2 Determine residual stem damage associated with the four harvesting systems.

3.3 Determine scar characteristics associated with residual stem damage from harvesting equipment.

3.4 Determine layout cost and residual stem damage associated with alternative layout methods.

3.5 Derive a production model using related significant, independent variables for four harvesting systems.

3.6 Derive a matrix of related costs, production rates, residual stem damage, and layout methods for four harvesting systems.

4.0 STUDY SITE DESCRIPTION

4.1 Study Site

The study site consisted of two, sixty-acre blocks on the northwest portion of the Warm Springs Indian Reservation (WSIR) located in the northern Cascades of Oregon (Figure 1). These blocks where part of the Long Willow Sale Area on the WSIR and were designated as Blocks 2 and 5 within this sale area (Figure 2). In Block 5, system 5DA was not logged by the harvest system planned due to adverse weather conditions. In addition, a narrow strip along the W-300 road was shovel-logged and not included in the study. These non-study areas removed approximately 20 acres from Block 5.

Both blocks originated from a large wildfire. Remnant old-growth Douglas-fir (*Pseudotsuga menziesii*) were scattered throughout the units, with noble fir (*Abies procera*) and Pacific silver fir (*A. amabilis*) naturally regenerated under the few remaining Douglas-fir. The stand averaged 70 years old, at breast height. Within the blocks were pockets of Douglas-fir that had been attacked by spruce budworm (SBW). Drought stress and SBW caused the Douglas-fir to be suppressed while the noble and Pacific silver firs became codominant. Slopes ranged from 0 to 25% with a variable aspect along the ridgeline. With an average elevation of 4600 ft above sea level, winter snowpack was high and summer precipitation low. In this climate, a minimal understory component was present.

Block 2 contained approximately 8 trees per acre (tpa) of old-growth Douglas-fir with large burls caused by withches'-broom. The Douglas-fir overstory was dying out, and a dense stand of second-growth noble and Pacific silver firs had developed. A preharvest volume of 50 thousand board feet (MBF) per acre was cruised. With an average dbh of 14 inches the noble fir retained 40% live crown. The plant association was ABAM/CLUN, Pacific silver fir/queencup beadlily (*Clintonia uniflora*).

Block 5 contained second-growth Douglas-fir and noble fir. Preharvest volume was 100 MBF per acre with an average dbh of 18 inches. Trees where tall, clear, and dense. The plant association was ABAM/CLUN.

Figure 1. Vicinity map.

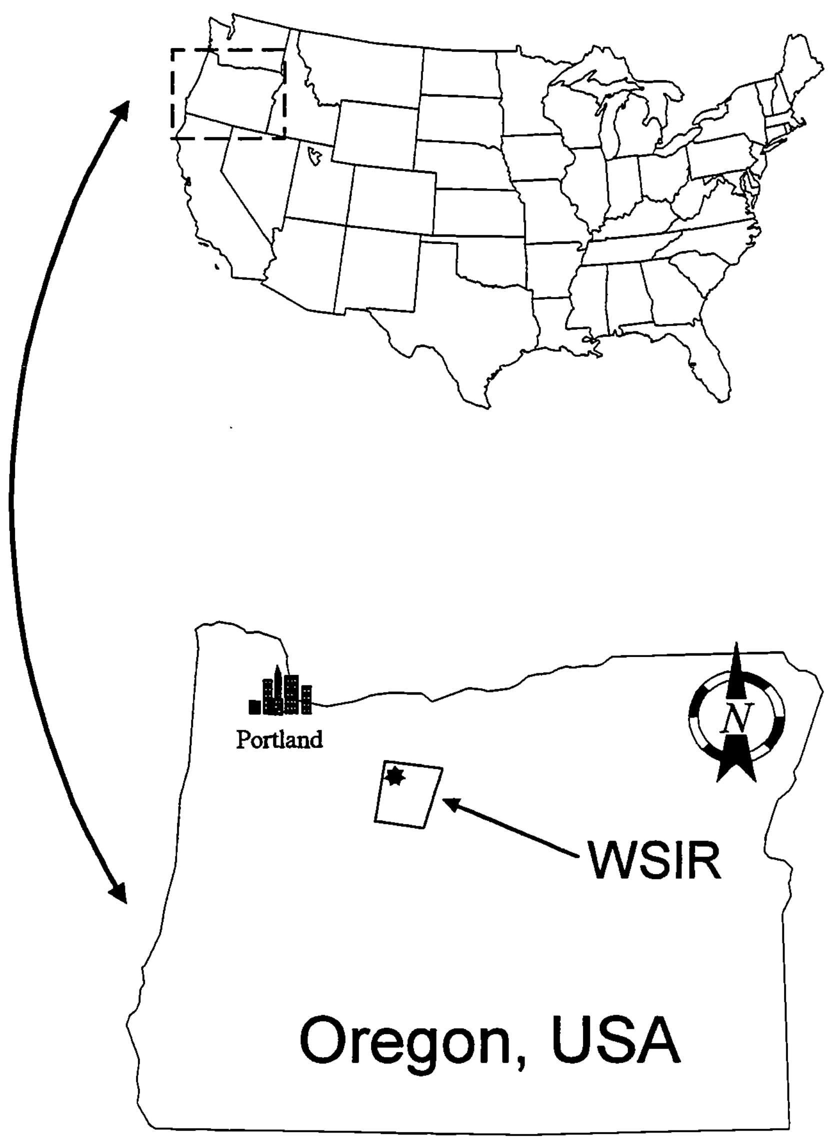
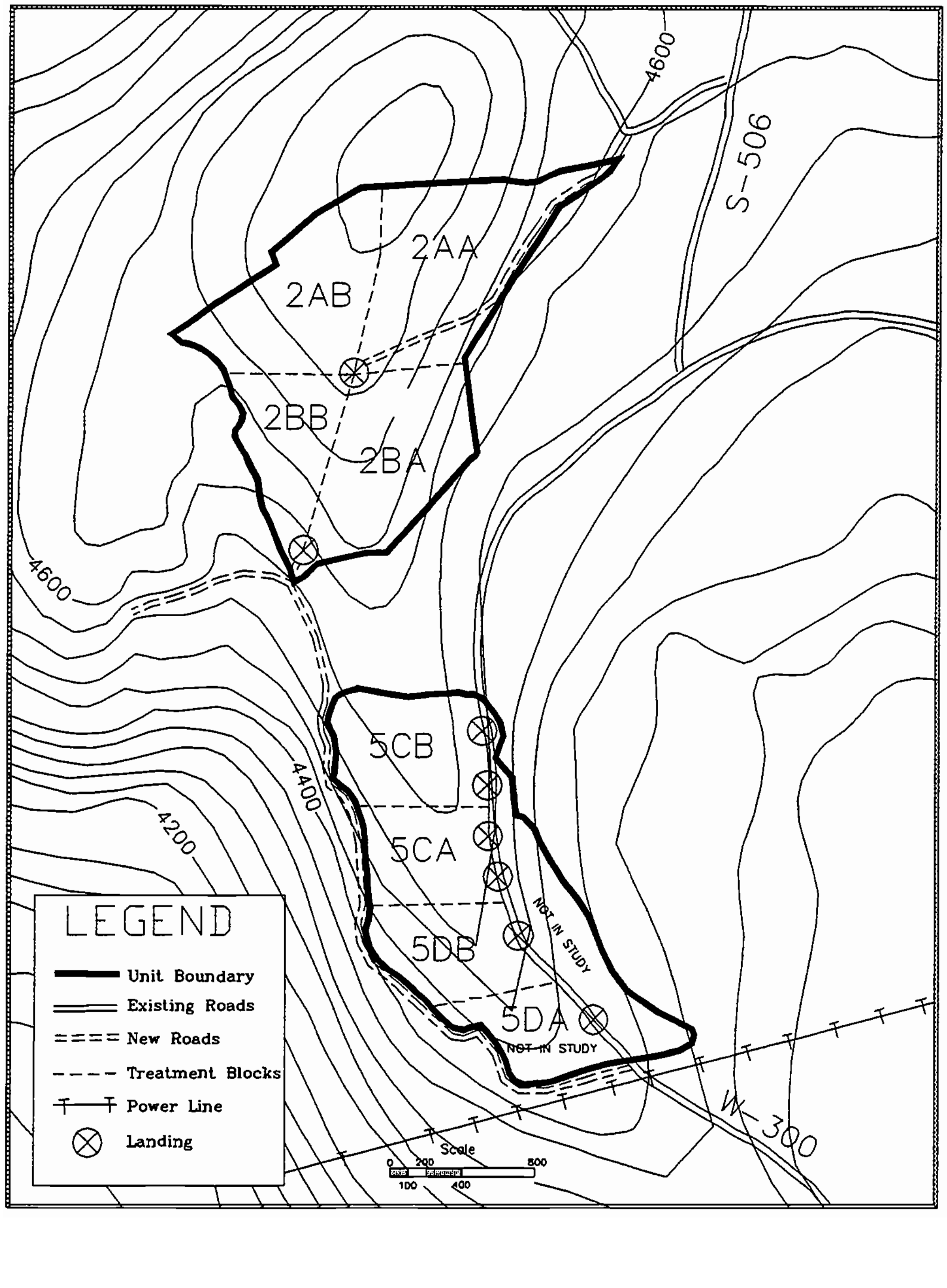


Figure 2. Unit map with harvesting block locations.



4.2 Silvicultural Prescription and Goals

The silvicultural prescription and stand management goals are those specified by the BIA (Arena 1996). The objectives for the two blocks were to leave healthy, dominant, and fast-growing trees of preferred species while reducing susceptibility to SBW. Thinning was generally from below. Spacing of the residual trees was based on a target basal area of 130 to 150 ft^2. This spacing was based on a relative density of 0.45, resulting in approximately 75 tpa.

The residual tree species, in order of preference, were:

1. Noble fir
2. Western white pine (*Pinus monticola*)
3. Douglas-fir
4. Lodgepole pine (*Pinus contorta*)
5. Grand fir (*Abies grandis*)
6. Pacific silver fir

Leave tree selection was based on characteristics such as:

1. Dominant or codominant
2. 30% crown ratio or greater
3. Disease free
4. Dense crown
5. Good Form

In addition, meeting preferred species and good leave-tree requirements had a higher priority than following spacing or free-to-grow guidelines. Along with residual crop trees, two large-diameter snags (≥20 inches dbh) and two cull trees for wildlife were left per acre. All leave trees were premarked based on the prescription above.

5.0 STUDY DESIGN

5.1 System Description and Specification

The selection of harvest systems was based on the current WSIR systems and on feasible systems that can be employed in the future. The systems selected for this are described Table in 1.

Table 1. Componets of harvest systems, desigantation and description.

Harvest System	Felling Operation	Primary Transportation	Landing Operation
A (feller-buncher)	Feller-buncher	Grapple skidder	Stroke-boom delimber, Log loader
B (shovel prebunching, partial-tree)	Manual felling	Shovel prebunching, Grapple skidder	Stroke-boom delimber, Log loader
C (shovel prebunching, log-length)	Manual felling, limbing, and bucking	Shovel prebunching, Grapple skidder	Log loader
D (winch line)	Manual felling, limbing, and bucking	Rubber-tired skidder equipped with a winch line	Log loader

5.1.1 *Harvest System A*

Harvest system A (feller-buncher) utilized a 1990 Cat 229 feller-buncher with a Pierce boom and Hultdin saw head. This particular head had a 36-inch felling bar capable of cutting a 34-inch tree with a single cut. The felling head had minimal mechanical control of the tree once it was severed from the stump. Trees were fell and bunched tree-length along trails for skidding by a 1996 Cat 525 fixed-boom grapple skidder (120-inch capacity). On a centralized landing, the trees were skidded to a 1989 Cat 225 with a Denis 3300 stroke-boom delimber. Limbs were removed and logs were bucked into appropriate lengths (depending on species and grade, but usually 40-ft long). Finally, logs were decked or loaded onto the log trucks by a 1989 Cat 225 hydraulic loader with a young boom.

5.1.2 *Harvest System B*

Harvest system B (shovel, partial-tree) utilized chainsaws for manually felling trees. The butt log was bucked (preferred log length was 40 ft) only if the tree length was greater than 80-ft. Logs, tree sections, and whole trees were then prebunched along skid trails with a 1990 Cat 229 log loader with a Pierce boom and grapples (shovel). These bunches were then skidded to a centralized landing by the 1996 Cat 525 grapple skidder. The stroke-boom delimbed and bucked the trees, and the logs were decked or loaded.

5.1.3 *Harvest System C*

Harvest system C (shovel, log-length) used the same bunching procedure as in system B, but all trees were limbed and bucked (preferred log length was 40 ft) after felling in the stand. The log bunches were skidded to roadside landings with the Cat 525 fixed-boom grapple skidder and a Cat 518 swing-boom grapple skidder (83-inch capacity). At the landing logs were decked or loaded onto the trucks.

5.1.4 *Harvest System D*

Harvest system D (winch line, log-length) used the same felling technique as system C, trees were felled to lead along skid trails. The Cat 525 and Cat 518 rubber-tired skidders used winch lines to extract logs from the stand to skid trails. The skidders were equipped with winch lines so skid trails with spacing of approximately 120 feet apart could be used. Logs were then skidded to a roadside landing and decked or loaded.

5.2 Layout Description

Each alternative harvesting systems (described above) was assigned to a 30-acre sub-harvest block. Then each sub-block was divided into two layout prescriptions (Table 2). The "conventional" prescription (A) was the practice currently used by the contract loggers. The "designated method", layout prescription B had the following features:

- Rub trees were identified or artificial tree protection was required.
- Skid trails were designated and marked prior to cutting.
- Skid trails were cut and cleared of logs before harvesting the stand.
- Directional felling techniques were used.
- Stumps were kept to a minimum height.

Table 2. Harvest system layout and treatment design.

	Block 2 Centralized landings		Block 5 Roadside landings	
Conventional Layout A	Harvest System A	Harvest System B	Harvest System C	Not Applicable
Designated Layout B	Harvest System A	Harvest System B	Harvest System C	Harvest System D

Along with two different layout prescriptions per harvesting system, the two blocks contained different designations for landing location and design. The first block (Block 2) contained centralized landings, whereas the second block (Block 5) had roadside landings.

6.0 STUDY METHODS

6.1 Study Techniques

Determining costs among alternative logging systems requires accurate production data. Collecting such data is challenging because of the variability within the logging environment (Olsen and Kellogg 1983). Production study methods need to provide information in order to calculate productive and non-productive time, break down productive time into cycle elements, and calculate interactions between equipment, personnel, and harvesting attributes. The methods used in this study were shift level studies, detailed time studies, and activity sampling.

6.1.1 *Shift Level Studies*

Shift level studies are daily production averages based on an observer's or worker's records of pieces handled and hours worked (Olsen and Kellogg 1983). In this study, each equipment operator and other key personnel were given a daily production form that was completed at the end of every shift. This included location, hours worked, delays, and production information (e.g. loads per day).

6.1.2 *Detailed Time Study*

With the recent advancement in small handheld computers or data collectors, it is easier to conduct detailed time studies. For this procedure, the time and conditions required for each turn (sequence of activities to bring a group of logs or trees to the landing) are recorded (Olsen and Kellogg 1983). Cycle components are timed, delays are broken out by cause, and independent variables (e.g. logs per turn and skidding distance) are recorded. This data is used later to generate regression and predictive equations for a sequence of cycles. A Husky Hunter (Husky Computer Limited 1989) was used along with SIWORK3 (Danish Institute of Forest Technology 1988) to conduct all detailed time studies.

6.1.3 *Activity Sampling*

Activity sampling measures the proportion of the workday spent on a series of activities by individual machines and people. In addition, it measures the interactions of equipment and personnel. Observations can be made at random times or at equally spaced intervals. The latter observations are called fixed-interval, systematic, group timing, or multi-moment sampling (Olsen and Kellogg 1983). The fixed-interval method is acceptable because of the variability in a logging operation (Olsen and Kellogg 1983), and was used along with multi-moment sampling in this study. An observation was made on a 20-second fixed interval for one hour at a time throughout the harvesting operation.

6.2 Specific Objectives

6.2.1 *Objective 3.1*

Determine production rates and cost per unit volume for four harvesting systems.

The production rates and cost per unit volume for the four systems were determined by the use of shift level and detailed time studies. Section 6.2.1.1 and 6.2.1.2

address both of these methods and outlines the dependent and independent variables that were studied.

6.2.1.1 Shift Level and Detailed Time Studies

Log volumes were determined by truck load ticket information. This was collected to monitor the volume removed per shift (from the loader's shift level form). An average log volume was calculated from the rollout scaling tickets at the mill by dividing the total load volume by the number of pieces per load.

All equipment operators and ground personnel completed a daily summary of their work and production (see Appendix F). Crew foremen, in charge of several workers, were responsible for the daily worker summary, which included:

- Date
- Unit #
- Treatment area
- Operator(s) name(s)
- Equipment description or number (if more than one was in use)
- Shift length
- Nonproductive time (> 10 minutes)
- Pieces handled (trees, logs, tops, etc.)
- # of skidding cycles or turns
- Average skidding distance
- General comments outlining the days production

The equipment operator or ground personnel used a mechanical counting device (tally counter) for keeping track of the pieces and cycles for the day's production. In addition, every worker on the site was given a detailed map that identified treatment boundaries. The shift level forms were collected weekly to ensure that they were being completed properly.

The detailed time study collected data on the dependent and independent variables for individual equipment in each harvesting unit. Each variable listed below is defined in Appendix A. The following are the dependent and independent variables used in the detail time study for individual equipment. In addition, past studies that the detailed time study was based upon are referenced.

Feller-buncher (Folkema 1977):

Dependent Variables	Independent Variables
Moving in stand	Treatment area
Felling cycle	DBH
Bunching	Number of trees
Brushing	
Delays	

Grapple skidder:

Dependent Variables	Independent Variables
Travel empty	Treatment area
Positioning	Distance traveled
Loading	Number of trees/turn
Reposition	Number of logs/turn
Travel loaded	Number of tops/turn
Unload	
Accumulate	
Delays	

Manual felling:

Dependent Variables	Independent Variables
Travel	Treatment area
Felling	Tree number
Measure and limb	Road
Buck	Method
Low stumping	
Delays	

Shovel (Ashby and Vaughan 1988):

Dependent Variables	Independent Variables
Travel	Treatment area
Acquire and Swing	% ground slope
Reposition	
Brushing	
Delays	

Rubber-tired skidder equipped with a winch line:

Dependent Variables	Independent Variables
Travel empty	Treatment area
Positioning	Distance traveled
Line out	Winch line distance
Line out and hook	Number of trees/turn
Winching	Number of logs/turn
Reposition	Number of tops/turn
Travel loaded	Number of chokers/turn
Unhook	Use of chaser on landing
Delays	

6.2.1.2 Production Rates and Cost per Unit Volume Calculations

A machine rate was calculated for each piece of equipment using a combination of data. The machine rate is defined as the hourly cost of ownership and operation for a machine or processes, including investment amortization, consumables, and labor costs (Lambert and Howard 1990). Cost of ownership for each piece of equipment was based on factors such as original investment, interest rates, salvage value, depreciation period, taxes, and insurance. Likewise, operating costs included, fuel and oil consumption, labor, and supervisory expenses (Mifflin 1980).

Productive costs of each machine were calculated by dividing machine rates by the corresponding production rate (Lambert and Howard 1990). Since all machines involved in the harvesting system had different production rates, all productive costs were determined independently. Therefore, the production cost of the entire harvest system was calculated by summing the productive cost of each machine (Lambert and Howard 1990). A computer software program called PACE, Production And Cost Evaluation (Sessions and Sessions 1986), was used to calculate owning and operating costs. The equations used in PACE are in Appendix B.

From the shift level and detailed time studies productive and nonproductive portions of a cycle were identified. Using multiple regression equations, the productive cycle time of specific timed equipment was determined for the different harvest blocks. The nonproductive cycle time was obtained from both the shift level (long-term delays, greater than 10 minutes) and detailed time study (short-term delays less than 10 minutes).

After the owning and operating costs were derived by PACE, the following attributes were used to calculate individual machine costs. Multiple regression equations from the detailed time study were used to predict the cycle times. Long and short-term delays from the shift level and detailed time study were calculated for individual equipment. A percent delay time was determined from both the shift level and detailed time study. These percentages were then combined and a percent delay time per scheduled machine hour (SMH) was calculated. Finally, the average piece size calculations (see section 7.1.2) were used to predict an average turn size. The final logging cost was determined for individual pieces of equipment using a modification of the cost tree diagram in Appendix G (Olsen 1994). A machine rate and cost process flow chart illustrates this methodology (Figure 3). The final individual harvesting cost was calculated as follows:

1. Turns per Hour, using multiple regression equations and delay analysis.

$$Effective\,Hour\,(\text{min}/\,hr) = 60\,\text{min} \times \left(1 - \%delay\,time\,per\,scheduled\,machine\,hour\,, SMH\right)$$

$$\frac{Turns}{Hour} = \frac{Effective\,Hour(\text{min}/\,hr)}{Total\,\text{Pr}oductive\,Cycle\,Time\,(\text{min}/\,turn)}$$

2. Turn Size, using detailed time studies and average piece size calculation.

$$\frac{MBF}{Turn} = \frac{net\,volume(MBF)}{piece} \times \frac{pieces}{turn}$$

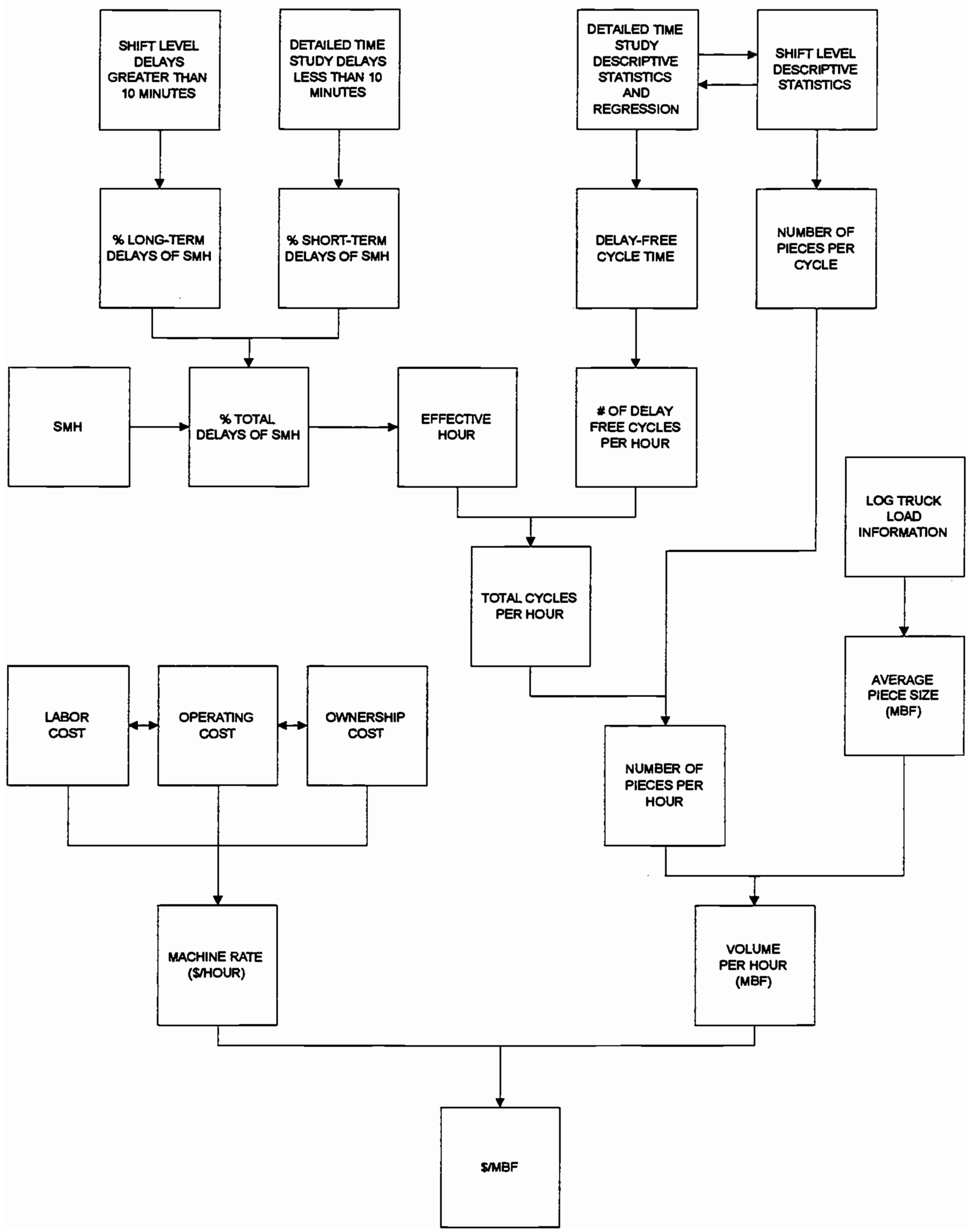
3. Production

$$\frac{MBF}{Hour} = \frac{Turns}{Hour} \times \frac{MBF}{Turn}$$

4. Final harvesting cost (by equipment), using PACE output.

$$\frac{\$}{MBF} = \frac{Owning\ \&\ Operating\,Cost(\$/\,hr)}{\frac{MBF}{Hour}}$$

Figure 3. Machine rate calculations and process flow chart.



6.2.2 *Objective 3.2*

Determine residual stem damage associated with harvesting systems.

The systematic circular plot method (Han and Kellogg 1997) was used to evaluate stand damage for each treatment. Scar size, height, gouge depth, and equipment causing the scar was recorded for each damaged tree.

The number of fixed-radius plots required for the survey was calculated by the following sample size equation (Thompson 1992).

$$n_o = \frac{N \times p(1-p)}{(N-1) \times \left(\frac{d^2}{z^2}\right) + p(1-p)}$$

$$\textit{Sample size for systematic sampling} = \frac{n_o}{t \times p \times s}$$

Where:

n_o = number of damaged trees required in sample

N = total number of trees in the unit. N is estimated by multiplying unit area by target number of trees to be left, e.g., N= 15 acres x 75 tpa = 1,125 trees

p = estimate of % damaged trees in unit. The formula depends on the unknown population proportion p. If no estimate of p is available prior to survey, a "worst case" value of p = 0.5 is used to determine sample size (Thompson 1992).

d = allowable sampling error, 15% in this study (d = 0.15)

z = the upper $\alpha/2$ point of the normal distribution (1.96 for 95% probability, α=0.05)

t = the estimated number of trees per acre

s = fixed-radius circle plot size, 0.1 acre or 0.2 acre

After the required number of damaged trees for sampling was determined an appropriate plot size was decided. By dividing the total number of trees (n_o) by the number of damaged trees per plot (e.g. 60 residual trees per acre = 12 trees per 1/5-acre plot) the total number of plots was calculated. This value was then rounded up to the nearest whole number.

For the purpose of this study, a 1/5 acre plot was used (52.7' radius). The number of plots were determined by using a residual tpa of 75 and an area of approximately 15 acres. The estimated total number of trees in each harvesting unit was 1125 trees. An estimated residual stand damage of 20% and a standard error of 15% were used, along with the t-value of 1.96. This resulted in estimates of 26.69 damaged residual trees for each block and 8.9 plots rounded to 9, 1/5-acre plots per harvest unit.

All plot centers and residual trees were located and tagged prior to any unit layout or harvesting. These plots were then visited after a piece of equipment had passed through an area and scar characteristics were recorded. The number of undamaged and damaged tree was recorded, and percent residual stand damage was then calculated by dividing the number of damaged tree by the total number of damaged and undamaged tree in each plot.

6.2.3 *Objective 3.3*

Determine scar characteristics associated with residual stem damage from harvesting equipment.

Comparisons were made on a harvesting unit and equipment level. The scar area, height, gouge depth, and piece of equipment causing the scar were reported. Scar area was measured on an incremental scale of 0.1 ft^2. Area gauges in 0.1 ft^2 intervals were used to estimate the scar size with a minimum-recorded size of 0.05 ft^2. Scar height was measured with a Spencer tape, leveling rod, or clinometer, and recorded to the nearest

0.5-ft. Because of the range in scar shapes and sizes, scar height was measured from the center of the scar area. Gouging was noted if the cambium had been broken. Depth was measured at or beneath the cambial surface, to the nearest centimeter, with a small metric ruler.

6.2.4 *Objective 3.4*

Determine layout cost and residual stem damage associated with alternative layout methods.

To determine the cost associated with residual stem damage, a shift level study was needed to track the time and cost associated with skid trail and unit layout (see Appendix F). The shift level data recorded were:

- Date
- Treatment area
- Crew members
- Person hours spent by the crew in:
    1. General reconnaissance
    2. Location and marking of skid trails
    3. Office analysis
    4. Residual tree selection and marking
    5. Sale administration

All hours recorded on the shift level form were specific to the layout of designated skid trails and trail location activities. Regular activities that the sale administrator and forest technicians were involved in were not recorded. However, residual tree selection and sale administration were recorded if the time involved was above and beyond the normal practice of the BIA. Finally, a cost associated with each layout treatment was determined and compared to the outcome of the stand damage survey.

6.2.5 *Objective 3.5*

Derive a production model using related significant, independent variables for four harvesting systems.

Derived by the program STATGRAPHICS Plus (Manugistics 1995), multiple linear regression was used to analyze the data from the detailed time study. The desired outcome from this was an equation to predict total productive time (TPT) for each piece of equipment in the study. To determine TPT, all delays were removed to achieve a delay-free cycle time.

A regression equation was developed for every piece of equipment in the detailed time study (if found to be significant). Using TPT as the dependent variable, all independent variables specific to a piece of equipment were entered into the regression equation. A combination of measured qualitative variables and indicator variables were used to represent the collected data. Running both a forward and backward stepwise regression, independent variables were eliminated. An F-value of 4 or a P-value greater than 0.05 was used as a basis for removing independent variables from the regression equation.

After the final model was determined, a series of trial-and-error runs were conducted by inserting individual variables back into the model to test for multi-colinearity. In addition, significant variables not pertinent to the prediction of TPT on a blockwise level were removed.

6.2.6 *Objective 3.6*

Derive a matrix for related costs, production rates, residual stem damage, and layout methods for four harvesting systems.

A combination of the detailed and shift level time studies, stand damage survey, and layout costs were used to accomplish the final objective. The matrix was derived to compare the alternative harvesting systems and layout methods to their associated costs and stand damage. The matrix compares and contrasts the following:

- Harvesting systems
- Layout prescriptions
- Production
- Residual stand damage

7.0 RESULTS

Two scenarios I and II were used to determine the overall cost of each harvest system. Scenario I was used for the primary discussion and comparison of the different systems. Scenario II shows the production and cost impacts from the actual volume removed and the effects of piece size on harvesting costs. These two scenarios best represented the conditions and feasibility of the observed operations.

7.1 Timber Obtained from Harvest

In this section, the harvest volume calculations for scenario I and II, load characteristics, and harvest product conversions are reported.

7.1.1 *Scenarios I and II: Average Piece Size Calculation*

Because of the variability and nature of standing timber, two approaches were taken to determine the average piece size for the harvesting systems. The two blocks, while close in proximity, varied in standing volume. To better compare the harvesting systems, two different volume calculations were made.

Scenario I followed the assumption that the harvested timber had the same tree size distribution over the two blocks. An average piece size was based on the weighted average of all log truckload tickets coming from the two blocks. The average net volume and number of pieces per load were determined for each sort. By using the number of truckloads per sort and the average volume per piece by sort, a weighted average piece size was determined. This was then used in cost calculations as the average piece size for all harvesting units in both blocks.

Scenario II used the same process for determining the average piece size based, however, on the scale tickets from individual harvesting units. This method better represented the true volume removed from each individual harvesting system in the two blocks, but did not allow for a good comparison of harvesting system productivity and cost. In this study, the average piece size for each harvesting system was either higher or lower than the overall average.

7.1.2 *Piece Size Calculation and Load Characteristics*

Five different log sorts left the study site. These sorts ranged from export logs to chip wood. The following is a summary of the different sorts along with the load characteristics and distribution between the harvest blocks:

Table 3 shows the distribution of five log sorts by the number of loads per harvesting unit.

Table 3. Distribution of log sorts (number of truck loads) by harvesting units.

Log Sorts[1]	2AA	2AB	2BA	2BB	5CA	5CB	5DB	Misc.	Total
1	16	23	17	24	1	5	0	0	86
2	11	12	9	16	25	13	0	0	86
3	31	29	14	8	0	0	0	0	82
4	0	0	24	51	63	44	50	40	272
5	33	35	27	30	23	11	9	15	184
Total	91	99	91	129	112	73	59	47	710

[1]Log sorts are defined by the following scale ticket number (xxx, load in series).

1. 009xxx, average DBH 6 inches, noble fire and Douglas-fir mix, weight scaled.
2. 035xxx, average DBH 10 inches, noble fir and Douglas-fir mix.
3. 113xxx, average DBH 14 inches, predominately noble fir.
4. 119xxx, average DBH 12 inches, noble fir and Douglas-fir mix.
5. 142xxx average DBH 8 inches, white fir mix (Pacific silver fir and grand fir).

Multiple regression was used to predict the volume and pieces per load for the five different sorts (Tables 4 and 5).

Table 4. Statistical summary of volume (bf) per load.

Log Sorts	Total Loads	Average b.f./load	Standard Error	p-value
1	86	2799	68.3	< .0001
2	86	4700	32.8	< .0001
3	82	5360	43.6	< .0001
4	272	5129	49.6	< .0001
5	184	4189	27.8	< .0001

Table 5. Statistical summary of pieces per load.

Log Sorts	Total Loads	Average pieces/load	Standard Error	p-value
1	86	113	0.70	< .0001
2	86	50	0.99	< .0001
3	82	26	1.00	< .0001
4	272	26	0.80	< .0001
5	184	60	0.86	< .0001

From this information, volume per load and volume per piece were calculated using the weighted average of number of loads and their respective volumes per harvest units. In addition, a weighted average was calculated for the entire study to derive an average volume per piece. Table 6 shows volume characteristics for individual harvesting units and for all units (TOTAL).

Table 6. Average volume (bf), # of pieces, and volume per piece by individual harvesting units and for all units (TOTAL).

	2AA	2AB	2BA	2BB	5CA	5CB	5DB	TOTAL[1]
Volume/load	4405.3	4271.0	4407.9	4438.0	4819.4	4751.4	4985.6	4577.9
# of pieces/load	56.5	61.1	54.7	53.1	39.1	41.4	31.2	48.3
bf/piece	111.3	102.2	118.4	123.3	146.5	147.9	177.8	131.9

[1]Average value for all harvesting units.

7.1.3 *Harvesting Products and Conversions*

Three different piece sizes: whole tree, partial tree, and log length, were produced (harvest system specific). The three processing methods produced a different average piece size per turn. A whole tree (no bucking) was the equivalent of 2.5 logs (harvest system A). The partial tree (butt log bucked) was equivalent to 1.5 logs (harvest system B). Finally, harvest systems C and D (entire tree bucked into logs) was equivalent to 1.0 logs. The conversion factors were used in determining the average volume per turn. To determine this, the number of pieces per turn was multiplied by the conversion factor to convert all lengths down to log-length (approximately 40-ft logs).

Different conversion factors were obtained by sampling the average number of logs or pieces produced for a specific harvest system's processing method that was skidded to the landing. Included in the conversions were the loss of volume due to breakage and a minimum merchantable top diameter of 6 inches.

7.2 Equipment Operations, Descriptive Statistics

The detailed time study data collected for each piece of equipment included the productive and nonproductive times, a statistical representation of the average cycle time, and a breakdown of components per cycle. The cycle times reported were total cycle time with delays (TCT) and total productive time without delays (TPT). The mean and standard deviation are provided for each independent and dependent variable included in the detailed time study. All dependent variables were reported in minutes and distance (ft) or pieces per cycle were reported for the independent variables. Refer to Tables 7 to 11 for variable values and Appendix A for variable definitions.

Table 7. Feller-buncher, descriptive statistics from detailed time study.

	Harvesting Units (Mean / Standard Deviation)			
	2AA		2AB	
TCT[1]	1.70	5.25	1.09	1.64
Travel[1]	0.24	0.52	0.27	0.81
Felling[1]	0.26	0.12	0.36	0.20
Bunching[1]	0.30	0.54	0.33	0.83
Brushing[1]	0.11	0.27	0.05	0.23
Delays[1]	0.80	4.85	0.08	0.49
TPT[1]	0.91	0.92	1.02	1.56
DBH[2]	13.2	4.90	13.7	4.40
# of Trees	1.10	0.20	1.10	0.25

[1]Values in minutes.
[2]Value in inches.

Table 8. Manual felling, descriptive statistics from detailed time study.

	Harvesting Units (Mean/Standard Deviation)									
	2BA		2BB		5CA		5CB		5DB	
TCT[1]	2.23	2.43	1.84	1.36	6.18	5.08	7.48	4.38	7.48	4.38
Travel[1]	0.41	0.24	034	0.26	0.39	0.35	1.26	0.92	1.26	0.92
Felling[1]	0.45	0.29	0.45	0.28	1.16	0.72	1.17	1.08	1.17	1.08
Limb[1]	0.35	0.55	0.36	0.46	1.66	1.19	2.45	1.51	2.45	1.51
Buck[1]	0.06	0.10	0.06	0.09	0.42	0.37	0.48	0.44	0.48	0.44
Low Stump[1]	0.04	0.20	0.08	0.20	0.25	0.34	0.36	0.30	0.36	0.30
Delays[1]	0.91	2.13	0.55	1.10	2.29	4.31	1.76	2.95	1.76	2.95
TPT1	1.32	0.93	1.29	0.92	3.89	1.96	5.72	2.88	5.72	2.88
DBH[2]	10.9	2.90	11.5	3.70	16.0	4.60	19.5	7.60	19.5	7.0

[1]Values in minutes.
[2]Value in inches.

Table 9. Shovel (prebunching), descriptive statistics from detailed time study.

	Harvesting Units (Mean/Standard Deviation)							
	2BA		2BB		5CA		5CB	
TCT[1]	1.59	1.66	1.70	4.56	1.33	3.86	0.87	0.87
Travel[1]	0.29	0.54	0.27	0.65	0.22	0.59	0.23	0.72
Acquire/Swing[1]	0.62	0.48	0.44	0.26	0.44	0.26	0.53	0.33
Reposition[1]	0.52	1.13	0.38	0.99	0.17	0.40	0.04	0.18
Brushing[1]	0.02	0.07	0.01	0.07	0.02	0.07	0.01	0.06
Delays[1]	0.14	0.52	0.59	4.12	0.48	3.43	0.06	0.19
TPT[1]	1.45	1.31	1.11	1.28	0.85	0.72	0.81	0.80

[1]Values in minutes.

Table 10. Grapple skidder, descriptive statistics from detailed time study.

	Harvesting Units (Mean/Standard Deviation)											
	2AA		2AB		2BA		2BB		5CA		5CB	
TCT[1]	6.47	3.39	9.39	13.5	6.70	7.23	7.86	9.59	6.30	10.2	5.79	8.81
Travel Empty[1]	1.38	0.46	1.36	0.38	1.27	0.43	1.48	0.40	0.69	0.31	0.77	0.36
Positioning[1]	0.32	0.43	0.45	0.20	0.49	0.22	0.56	0.42	0.50	0.25	0.44	0.19
Loading[1]	0.39	0.20	0.48	0.22	0.54	0.23	0.52	0.26	0.51	0.18	0.48	0.17
Accumulate[1]	0.90	1.61	0.22	0.68	0.33	0.84	0.51	1.00	0.21	0.87	0.15	0.62
Reposition[1]	0.19	0.44	0.02	0.08	0.12	0.36	0.04	0.13	0.05	0.21	0.11	0.58
Travel Loaded[1]	1.51	0.54	1.51	0.46	1.22	0.42	1.36	0.38	0.76	0.33	0.84	0.36
Unload[1]	0.65	0.18	0.59	0.14	0.62	0.19	0.55	0.19	0.44	0.18	0.46	0.14
Delays[1]	1.12	2.57	4.77	13.4	2.12	6.98	2.85	9.49	3.15	10.2	2.54	8.64
TPT[1]	5.35	2.23	4.62	1.06	4.59	1.12	5.01	1.22	3.15	1.07	3.25	1.09
Distance[2]	436	200	486	135	401	152	497	154	272	123	302	140
# of Trees	4.50	4.20	7.30	3.20	1.20	0.90	1.20	1.10	0.04	0.20	0.04	0.20
# of Logs	0.60	1.00	0.50	2.10	7.30	2.60	6.50	2.40	9.30	2.63	8.80	2.70
# of Tops	0.10	0.40	0.10	0.40	0.50	0.70	0.90	1.00	0.10	0.30	0.10	0.40

[1]Values in minutes.
[2]Value in ft.

Table 11. Rubber-tired skidder with winch line, descriptive statistics from detailed time study.

Harvesting Units 5DB (Mean/Standard Deviation)		
TCT[1]	15.32	9.84
Travel Empty[1]	0.88	0.34
Positioning[1]	0.69	0.34
Line Out[1]	4.68	1.73
Hook[1]	1.22	0.86
Winching[1]	0.36	0.18
Reposition[1]	0.40	0.66
Travel Loaded[1]	1.04	0.46
Unhook[1]	1.68	0.53
Delays[1]	2.26	13.21
TPT[1]	13.07	16.01
Skid Distance[2]	328	133
Winch Distance[2]	26.3	9.4
# of Choker	4.10	1.00
# of Trees	0.00	0.00
# of Logs	4.30	1.20
# of Tops	0.20	0.70

[1]Values in minutes.
[2]Values in ft.

7.3 Harvesting Production Rates and Cost

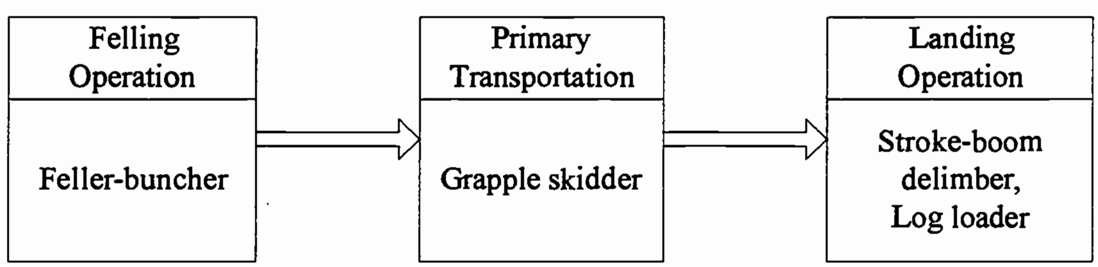
The following sections report the production and harvesting cost for each piece of equipment, and the total harvesting cost for each system. Other aspects of the operation, including indirect-harvesting, equipment-related costs were chaser, laborer, pickups, fire protection, etc. were cost out based on total SMH. The complete harvesting cost reports are in appendix E.

All harvesting costs for each harvesting unit and scenario were broken down by equipment and tasks. The total harvesting cost was based on the following variables: felling operation, primary transportation, landing operation, crew transportation, fire protection, planning, and layout. There was no hauling cost or profit and risk allowance included in the total harvesting cost.

7.3.1 *Harvest System A*

Harvest system A consisted of the following equipment shown in Figure 4.

Figure 4. Harvest system A, equipment flow chart.



Based on the detailed time studies, Table 12 shows the multiple regression equation for total productive time (TPT) per cycle for the grapple skidder. Taking into account the significant variables, the TPT was predicted for the different harvest systems. An average slope skidding distance of 400 ft was used in the regression equation for all systems. The regression equation for the feller-buncher had no significant variables and was not used to determine TPT. Shift level forms were used to determine production rates for all other equipment not included in the regression analysis.

Table 12. Multiple regression for grapple skidder, used for all harvest systems.

Independent Variables:		p-value
Constant = log length and conventional		< 0.0001
Tree length = 0, 1 indicator		< 0.0001
Partial tree = 0, 1 indicator		< 0.0001
Designated skid trail 0, 1 indicator		0.0206
Distance = 400 ft		< 0.0001
Regression Equation:	TPT = 188.9 + 73.2 * tree length + 81.6 * partial tree - 30.6 * designated + 0.5 * distance	< 0.0001 R^2 = 52.9

The harvesting costs for Scenarios I and II for systems 2AA and 2AB are shown in Tables 13 to 16.

Table 13. Harvesting costs for harvest unit 2AA, Scenario I (feller-buncher; conventional).

Equipment	Machine Rate ($/hour)	Production (MBF/hour)	Cost ($/MBF)
Feller-buncher	132.45	11.52	11.50
Grapple Skidder	62.65	14.93	4.20[1]
Delimber	118.15	10.77	10.97
Loader	81.07	3.30	24.57
Swing-boom	21.89	4.01	5.46
Chaser	20.00	4.01	4.99
Laborer	20.00	4.01	4.99
Pickups	12.48	4.01	3.11
Chainsaw/Fire	2.81	4.01	0.70
Layout	0.27	4.01	0.07
Move In	2.62	4.01	0.65
TOTAL HARVESTING COST			71.21

[1]Used regression equation in determining equipment cost ($/MBF).

Table 14. Harvesting costs for harvest unit 2AB, Scenario I (feller-buncher; designated).

Equipment	Machine Rate ($/hour)	Production (MBF/hour)	Cost ($/MBF)
Feller-buncher	132.45	16.09	8.23
Grapple Skidder	62.65	13.98	4.48
Delimber	118.15	13.08	9.03
Loader	81.07	3.14	25.82
Swing-boom	21.89	4.12	5.31
Chaser	20.00	4.12	4.85
Laborer	20.00	4.12	4.85
Pickups	12.48	4.12	3.03
Chainsaw/Fire	2.81	4.12	0.68
Layout	2.73	4.12	0.66
Move In	3.34	4.12	0.81
TOTAL HARVESTING COST			67.75

Table 15. Harvesting costs for harvest unit 2AA, Scenario II (feller-buncher; conventional).

Equipment	Machine Rate ($/hour)	Production (MBF/hour)	Cost ($/MBF)
Feller-buncher	132.45	9.70	13.66
Grapple Skidder	62.65	12.57	4.98
Delimber	118.15	9.07	13.03
Loader	81.07	3.18	25.49
Swing-boom	21.89	3.85	5.69
Chaser	20.00	3.85	5.19
Laborer	20.00	3.85	5.19
Pickups	12.48	3.85	3.24
Chainsaw/Fire	2.81	3.85	0.73
Layout	0.27	3.85	0.07
Move In	2.62	3.85	0.68
TOTAL HAVESTING COST			77.95

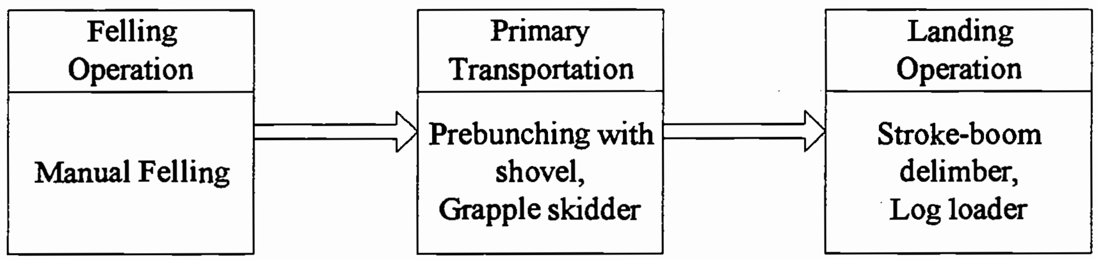
Table 16. Harvesting costs for harvest unit 2AB, Scenario II (feller-buncher; designated).

Equipment	Machine Rate ($/hour)	Production (MBF/hour)	Cost ($/MBF)
Feller-buncher	132.45	12.45	10.64
Grapple Skidder	62.65	10.81	5.79
Delimber	118.15	10.12	11.68
Loader	81.07	2.93	27.67
Swing-boom	21.89	3.84	5.70
Chaser	20.00	3.84	5.20
Laborer	20.00	3.84	5.20
Pickups	12.48	3.84	3.25
Chainsaw/Fire	2.81	3.84	0.73
Layout	2.73	3.84	0.71
Move In	3.34	3.84	0.87
TOTAL HARVESTING COST			77.44

7.3.2 *Harvest System B*

Harvest System B consisted of the following equipment shown in Figure 5.

Figure 5. Harvest system B, equipment flow chart.



Regression equations for TPT for manual felling and the shovel for prebunching are shown in Tables 17 and 18. The manual felling regression equations used an average DBH of 12 inches, and the number of pieces per turn (pieces) for the shovel was 1 per cycle. Shift level forms were used to determine production rates for all other equipment not included in the regression analysis.

Table 17. Multiple regression for manual felling, used for all harvesting systems.

Independent Variables:	p-value
constant = log length and conventional	< 0.0001
Partial tree = 0, 1 indicator	< 0.0001
Designated = 0, 1 indicator	0.0038
dbh = 12 inches	< 0.0001
Regression Equation: TPT = 318.6 - 306.2 * partial + 75.2 * designated + 6.3 * dbh	< 0.0001 $R^2 = 46.8$

Table 18. Multiple regression for Shovel, used for all harvesting systems.

Independent Variables:	p-value
Constant = log length	< 0.0330
Partial tree = 0, 1 indicator	< 0.0099
Pieces = 1 per cycle	< 0.0001
Regression Equation: TPT = 32.7 + 37.1 * partial + 29.2 * pieces	< 0.0001 $R^2 = 11.5$

The harvesting costs for Scenarios I and II in harvest systems 2BA and 2BB are shown in Tables 19 to 22.

Table 19. Harvesting costs for harvest unit 2BA, Scenario I (shovel prebunching; partial-tree; conventional).

Equipment	Machine Rate ($/hour)	Production (MBF/hour)	Cost ($/MBF)
Manual Felling	45.00	12.00	3.75[1]
Shovel	121.51	5.57	21.83[1]
Grapple Skidder	62.65	9.00	6.96[1]
Delimber	118.15	8.97	13.18
Loader	81.07	3.59	22.59
Swing-boom	21.89	4.98	4.40
Chaser	20.00	4.98	4.02
Laborer	20.00	4.98	4.02
Pickups	12.48	4.98	2.51
Chainsaw/Fire	2.81	4.98	0.56
Layout	0.31	4.98	0.06
Move In	3.06	4.98	0.61
TOTAL HARVESTING COST			84.48

[1]Used regression equation in determining equipment cost ($/MBF).

Table 20. Harvesting costs for harvest unit 2BB, Scenario I (shovel prebunching; partial-tree; designated).

Equipment	Machine Rate ($/hour)	Production (MBF/hour)	Cost ($/MBF)
Manual Felling	45.00	7.24	6.22
Shovel	121.51	4.38	27.74
Grapple Skidder	62.65	11.52	5.44
Delimber	118.15	9.89	11.95
Loader	81.07	3.82	21.22
Swing-boom	21.89	5.44	4.02
Chaser	20.00	5.44	3.68
Laborer	20.00	5.44	3.68
Pickups	12.48	5.44	2.30
Chainsaw/Fire	2.81	5.44	0.52
Layout	3.41	5.44	0.63
Move In	3.34	5.44	0.61
TOTAL HARVESTING COST			88.01

Table 21. Harvesting costs for harvest unit 2BA, Scenario II (shovel prebunching; partial-tree; conventional).

Equipment	Machine Rate ($/hour)	Production (MBF/hour)	Cost ($/MBF)
Manual Felling	45.00	10.78	4.18
Shovel	121.51	5.00	24.30
Grapple Skidder	62.65	8.08	7.76
Delimber	118.15	8.05	14.67
Loader	81.07	3.45	23.50
Swing-boom	21.89	4.79	4.57
Chaser	20.00	4.79	4.17
Laborer	20.00	4.79	4.17
Pickups	12.48	4.79	2.60
Chainsaw/Fire	2.81	4.79	0.59
Layout	0.31	4.79	0.06
Move In	3.06	4.79	0.64
TOTAL HARVESTING COST			91.19

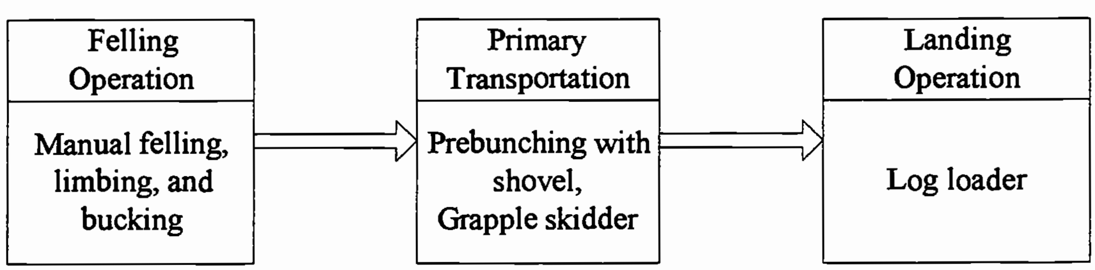
Table 22. Harvesting costs for harvest unit 2BB, Scenario II (shovel prebunching; partial tree; designated).

Equipment	Machine Rate ($/hour)	Production (MBF/hour)	Cost ($/MBF)
Manual Felling	45.00	6.75	6.67
Shovel	121.51	4.09	29.72
Grapple Skidder	62.65	10.75	5.83
Delimber	118.15	9.23	12.81
Loader	81.07	3.70	21.92
Swing-boom	21.89	5.27	4.15
Chaser	20.00	5.27	3.79
Laborer	20.00	5.27	3.79
Pickups	12.48	5.27	2.37
Chainsaw/Fire	2.81	5.27	0.53
Layout	3.41	5.27	0.65
Move In	3.34	5.27	0.63
TOTAL HARVESTING COST			92.85

7.3.3 *Harvest System C*

Harvest system C consisted of the following equipment shown in Figure 6.

Figure 6. Harvest system C, equipment flow chart.



Although the regression equation was the same as for harvest system B, different indicator variables were used for predicting TPT. Because two different grapple skidders were used in this harvest system, a weighted average skidding cost was determined. The two skidders had different operating costs and production rates so their costs were individually broken out. These costs were based on the portion of time each spent skidding logs to the landing. Shift level forms were used to determine production rates for all other equipment not included in the regression analysis. The harvesting cost for Scenarios I and II in harvest systems 5CA and 5CB are shown in Tables 23 to 26.

Table 23. Harvesting costs for harvest unit 5CA, Scenario I (shovel prebunching; log-length; conventional).

Equipment	Machine Rate ($/hour)	Production (MBF/hour)	Cost ($/MBF)	Average Skidding Cost
Manual Felling	45.00	3.05	14.75[2]	
Shovel	121.51	4.65	26.13[2]	
Grapple Skidder	62.65	9.28	6.75[2]	3.71[1]
Swing-boom	57.17	3.72	15.37	6.91[1]
Loader	81.07	4.91	16.51	
Delimber	118.15	6.90	17.12	
Chaser	20.00	6.90	2.90	
Pickups	12.48	6.90	1.81	
Chainsaw/Fire	2.81	6.90	0.41	
Layout	1.07	6.90	0.16	
Move In	6.99	6.90	1.01	
TOTAL HARVESTING COST				91.42

[1]Weighted average of skidding costs (3.71 and 6.91) was used to determine total skidding cost per MBF.
[2]Used regression equation in determining equipment cost ($/MBF).

Table 24. Harvesting costs for harvest unit 5CB, Scenario I (shovel prebunching; log length; designated).

Equipment	Machine Rate ($/hour)	Production (MBF/hour)	Cost ($/MBF)	Average Skidding Cost
Manual Felling	45.00	2.53	17.79	
Shovel	121.51	8.40	14.47	
Grapple Skidder	62.65	9.47	6.62	1.19[1]
Swing-boom	57.17	2.75	20.79	17.03[1]
Loader	81.07	4.54	17.86	
Delimber	118.15	6.58	17.96	
Chaser	20.00	6.58	3.04	
Pickups	12.48	6.58	1.90	
Chainsaw/Fire	2.81	6.58	0.43	
Layout	1.88	6.58	0.29	
Move In	4.59	6.58	0.70	
TOTAL HARVESTING COST				92.66

[1]Weighted average of skidding costs (1.19 and 17.03) was used to determine total skidding cost per MBF.

Table 25. Harvesting costs for harvest unit 5CA, Scenario II (shovel prebunching; log length; conventional).

Equipment	Machine Rate ($/hour)	Production (MBF/hour)	Cost ($/MBF)	Average Skidding Cost
Manual Felling	45.00	3.41	13.20	
Shovel	121.51	5.19	23.42	
Grapple Skidder	62.65	10.35	6.05	3.33[1]
Swing-boom	57.17	4.15	13.77	6.20[1]
Loader	81.07	5.16	15.70	
Delimber	118.15	7.23	16.34	
Chaser	20.00	7.23	2.77	
Pickups	12.48	7.23	1.73	
Chainsaw/Fire	2.81	7.23	0.39	
Layout	1.07	7.23	0.15	
Move In	6.99	7.23	0.97	
TOTAL HARVESTING COST				84.20

[1]Weighted average of skidding costs (3.33 and 6.20) was used to determine total skidding cost per MBF.

Table 26. Harvesting cost for harvest unit 5CB, Scenario II (shovel prebunching; log-length; designated).

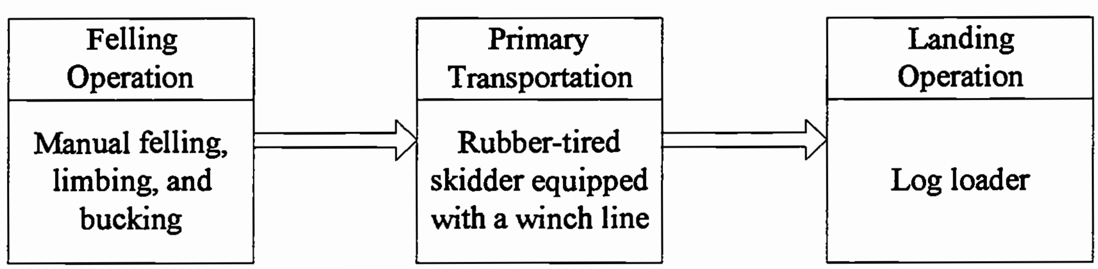
Equipment	Machine Rate ($/hour)	Production (MBF/hour)	Cost ($/MBF)	Average Skidding Cost
Manual Felling	45.00	2.83	15.90	
Shovel	121.51	9.43	12.89	
Grapple Skidder	62.65	10.63	5.90	1.06[1]
Swing-boom	57.17	3.09	18.51	15.18[1]
Loader	81.07	4.71	17.21	
Delimber	118.15	6.83	17.30	
Chaser	20.00	6.83	2.93	
Pickups	12.48	6.83	1.83	
Chainsaw/Fire	2.81	6.83	0.41	
Layout	1.88	6.83	0.28	
Move In	4.59	6.83	0.67	
TOTAL HARVESTING COST				85.63

[1]Weighted average of skidding costs (1.06 and 15.81) was used to determine total skidding cost per MBF.

7.3.4 *Harvest System D*

Harvest system D consisted of the following equipment shown in Figure 7.

Figure 7. Harvest system D, equipment flow chart.



Using the regression equation for the rubber-tired skidder equipped with a winch line (Table 27) along with the manual felling regression equation (Table 17), TPT was determined. An average slope skidding distance of 400 ft and 4 logs per cycle were used. Shift level forms were used to determine production rates for all other equipment not included in the regression analysis.

Table 27. Multiple regression for rubber-tired skidder equipped with a winch line.

Independent Variables:	p-value
Constant = log length and designated	0.0010
Distance = 400 feet	0.0008
Logs = 4 per cycle	< 0.0001
Regression Equation: TPT = 405.7 + 0.8 * distance + 100.7 * logs	< 0.0001 R^2 = 38.0

The harvesting costs for Scenarios I and II for harvest system 5DB are shown in Tables 28 and 29.

Table 28. Harvesting costs for harvest unit 5DB, Scenario I (winch line; log-length; designated).

Equipment	Machine Rate ($/hour)	Production (MBF/hour)	Cost ($/MBF)	Average Skidding Cost
Manual Felling	45.00	3.11	14.47[2]	
Grapple-Winch	62.65	2.48	25.26[2]	16.16[1]
Swing-Winch	57.17	1.99	28.73	10.34[1]
Loader	81.07	3.57	22.71	
Chaser	20.00	5.04	3.97	
Pickups	12.48	5.04	2.48	
Chainsaw/Fire	2.81	5.04	0.56	
Layout	1.46	5.04	0.29	
Move In	4.08	5.04	0.81	
TOTAL HARVESTING COST				71.79

[1]Weighted average of skidding costs (16.16 and 10.34) was used to determine total skidding cost per MBF.
[2]Used regression equation in determining equipment cost ($/MBF).

Table 29. Harvesting costs for harvest unit 5DB, Scenario II (rubber-tired skidder equipped with a winch line; log-length; designated).

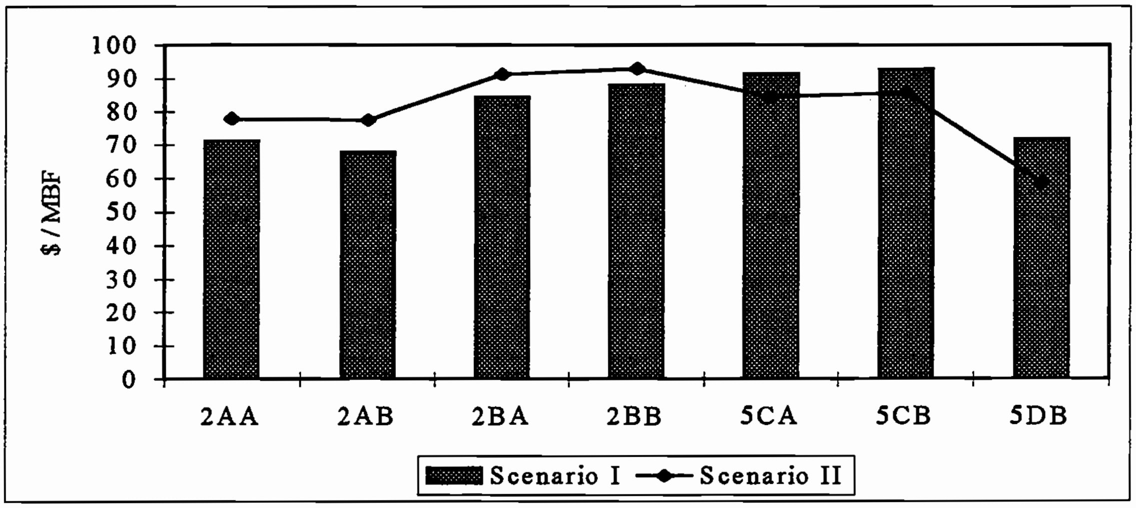
Equipment	Machine Rate ($/hour)	Production (MBF/hour)	Cost ($/MBF)	Average Skidding Cost
Manual Felling	45.00	4.20	10.70	
Grapple-Winch	62.65	3.35	18.70	11.97[1]
Swing-Winch	57.17	2.69	21.25	7.66[1]
Loader	81.07	3.88	20.88	
Chaser	20.00	5.48	3.65	
Pickups	12.48	5.48	2.28	
Chainsaw/Fire	2.81	5.48	0.51	
Layout	1.46	5.48	0.27	
Move In	4.08	5.48	0.74	
TOTAL HARVESTING COST				58.66

[1]Weighted average of skidding costs (11.97 and 7.66) was used to determine total skidding cost per MBF.

7.3.5 *Final Harvesting Cost Summary*

The total harvesting cost per MBF is summarized in Figure 8.

Figure 8. Total harvesting cost per harvest unit for Scenarios I and II.



7.4 Landing Operations

Based on the activity sample, landing operations were studied and percent time involved in each predetermined activity category was recorded. For Block 2 centralized landings were used, whereas roadside landings were constructed in Block 5 Figures 9 and 10.

Figure 9. Centralized landing design and boundaries for Block 2.

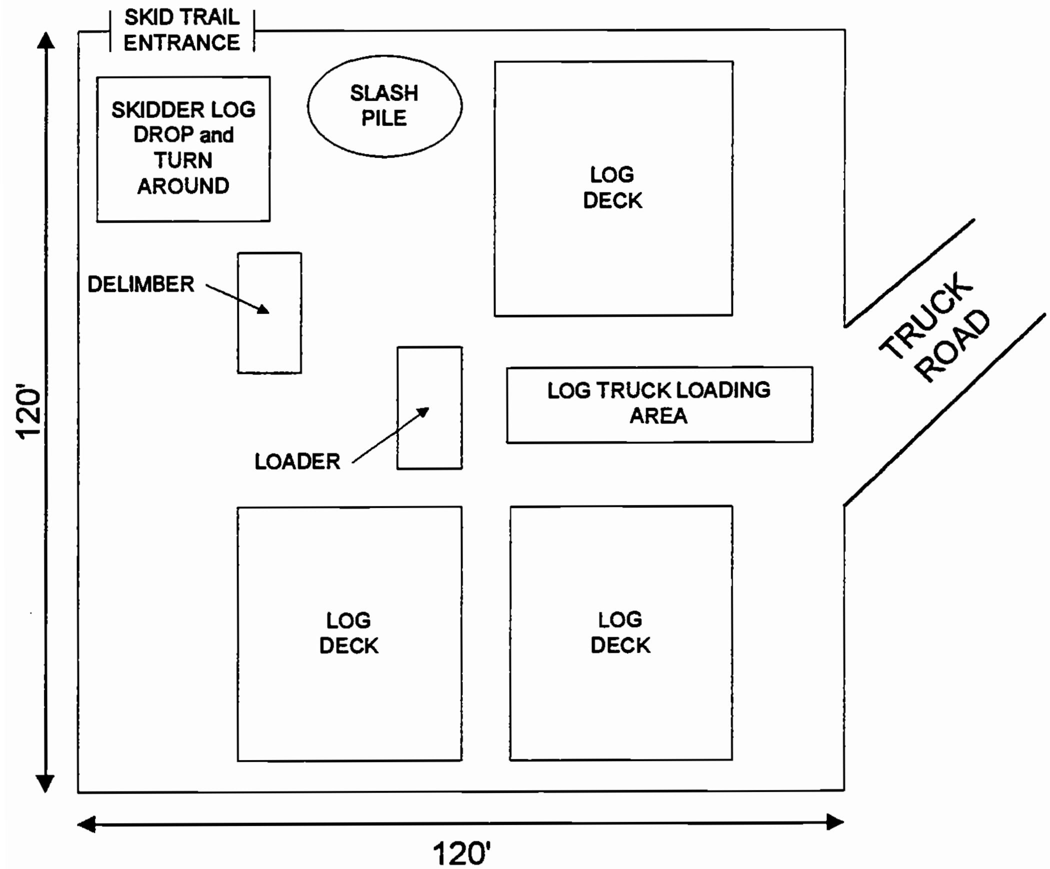
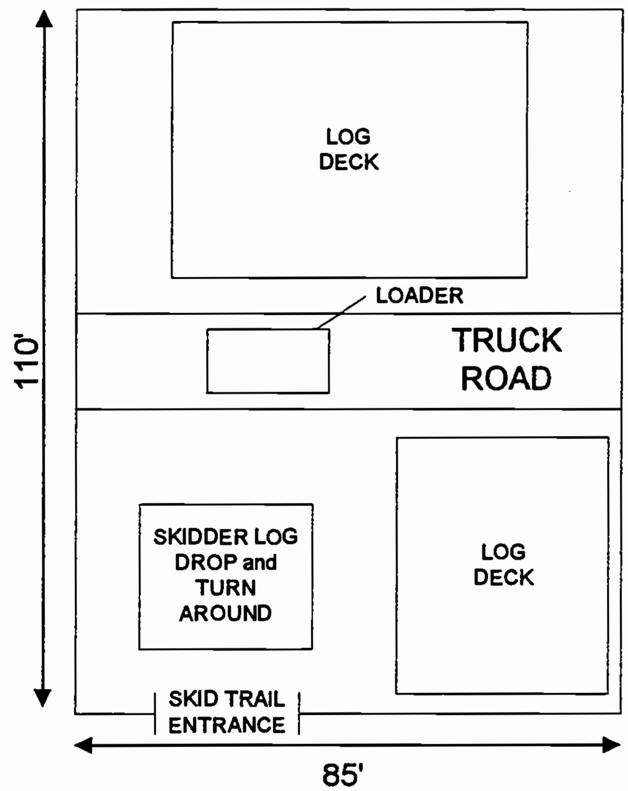


Figure 10. Roadside landing design and boundaries for Block 5.



The percent time that each piece of equipment spent in activities for the two landing designs is shown in Figures 11 to 15. Variable definitions are found in Appendix A.

Figure 11. Percent time spent by loader in different landing activities.. A) Centralized landings and B) Roadside landings.

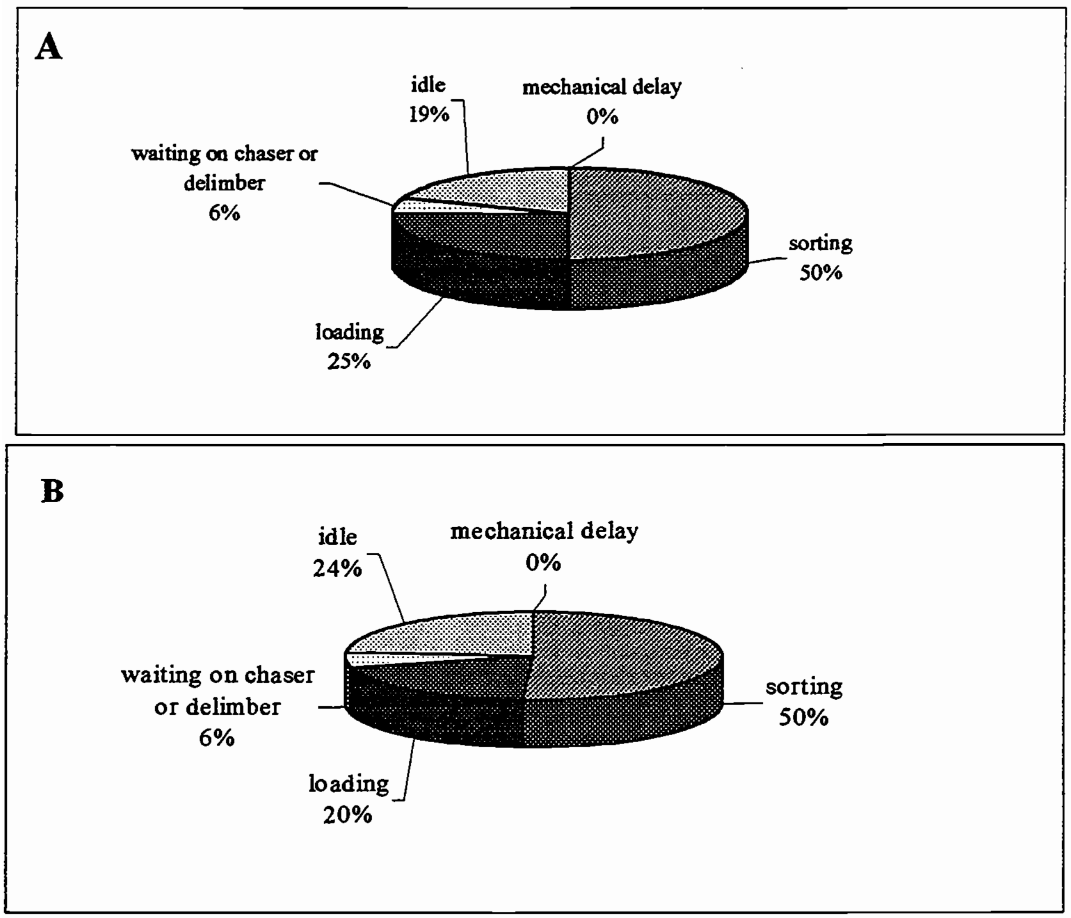


Figure 12. Percent time spent by the delimber in different landing activities at centralized landings.

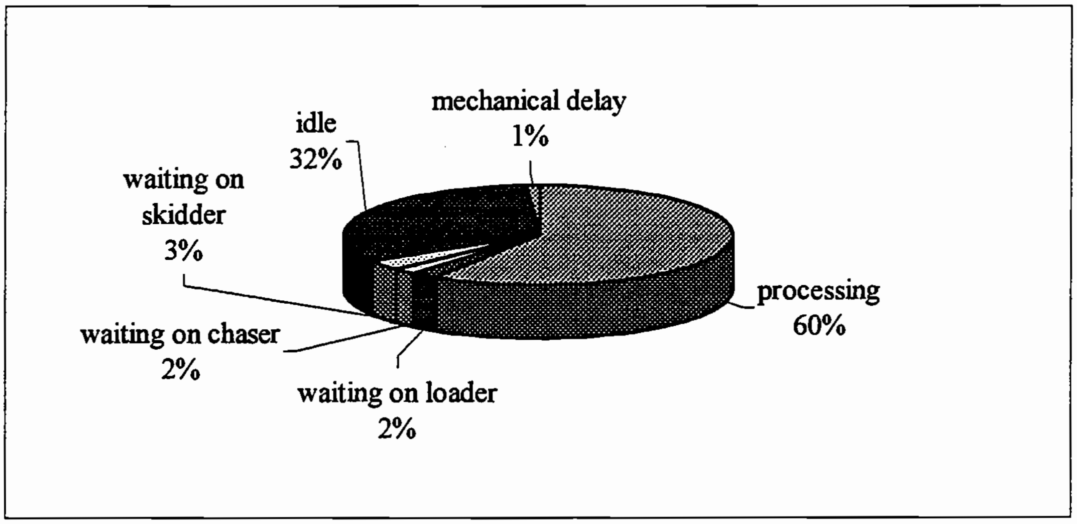


Figure 13. Percent time spent by the skidder in different landing activities. A) Centralized landings and B) Roadside landings.

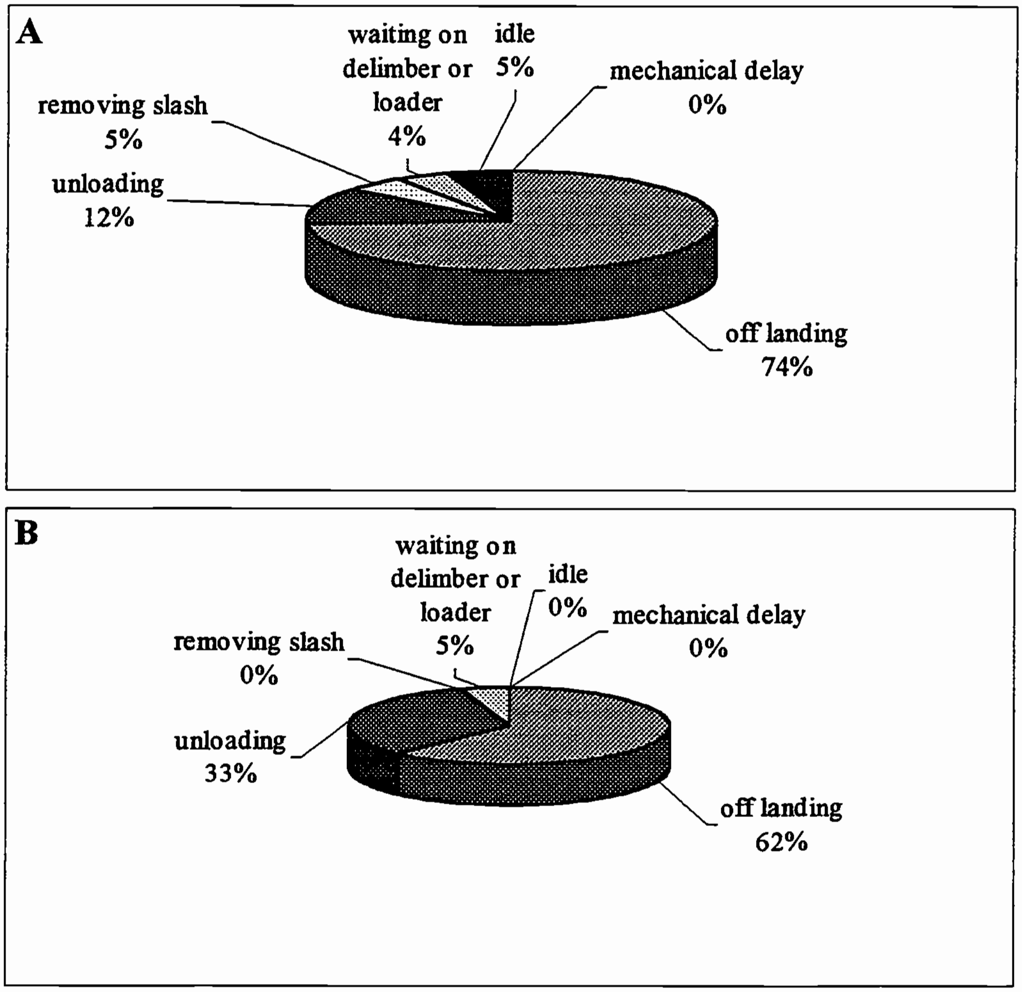


Figure 14. Percent time spent by the log trucks in different landing activities. A) Centralized landings and B) Roadside landings.

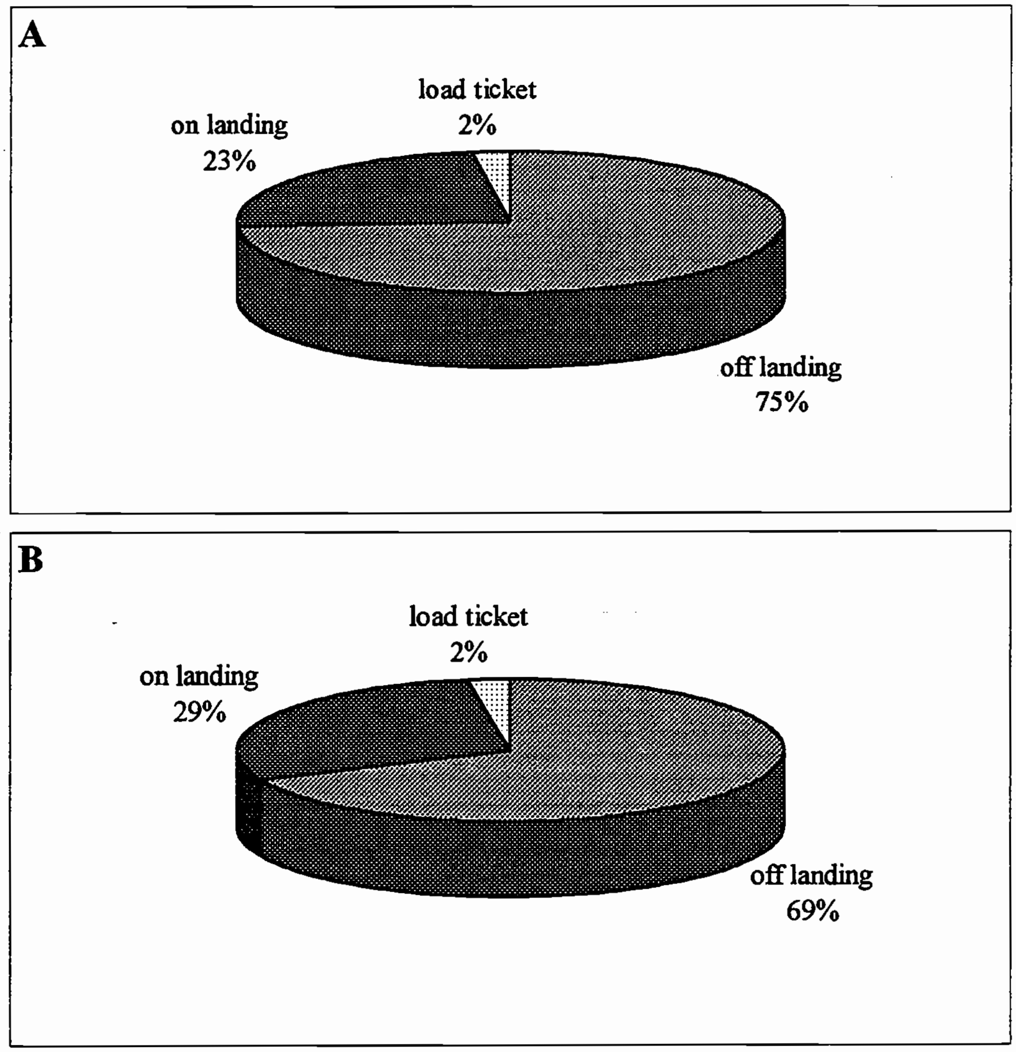
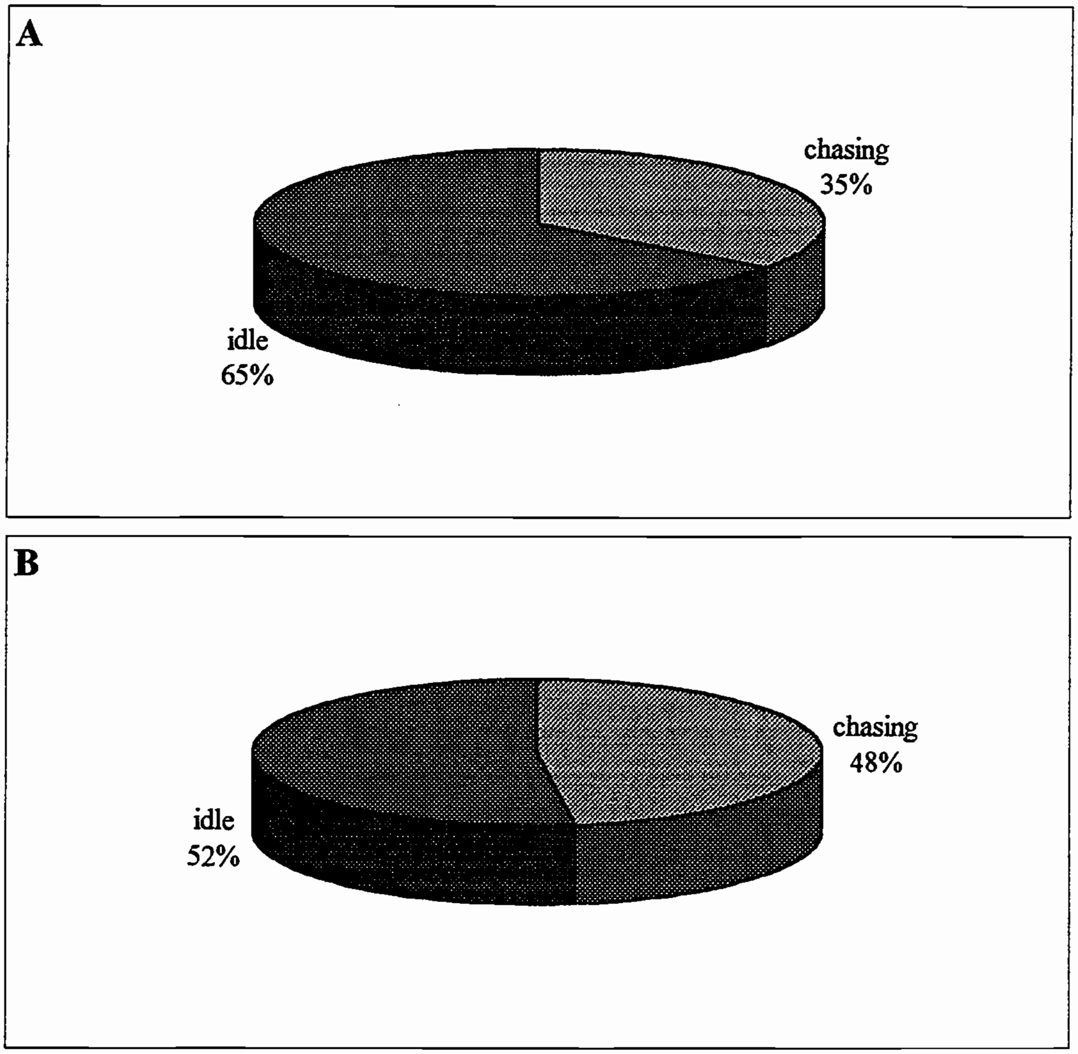


Figure 15. Percent time spent by the chaser in different landing activities. A) Centralized landings and B) Roadside landings.



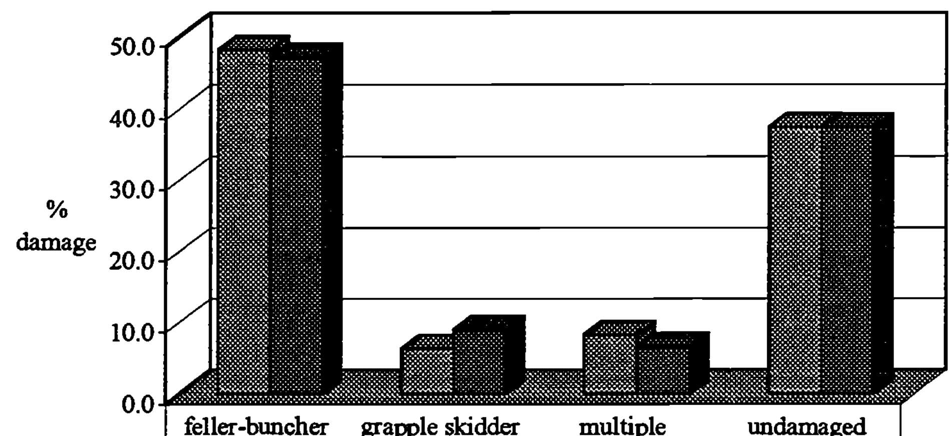
7.5 Stand Damage: Descriptive Statistics

The following sections report on the stand damage survey results: mean, standard error, minimum and maximum values for scar characteristics related to each piece of equipment or harvesting unit are summarized. Finally, a measure of scar severity is determined for each harvesting unit on an individual tree basis.

7.5.1 *Residual Stand Damage by Block*

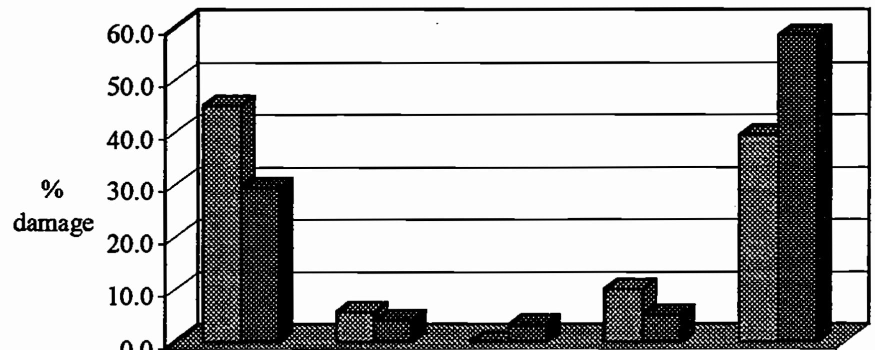
Residual damage per harvest unit, related to harvesting equipment, is shown in Figures 16 to 19.

Figure 16. Percent residual stand damage by equipment and layout design, harvest system A (feller-buncher; whole-tree).



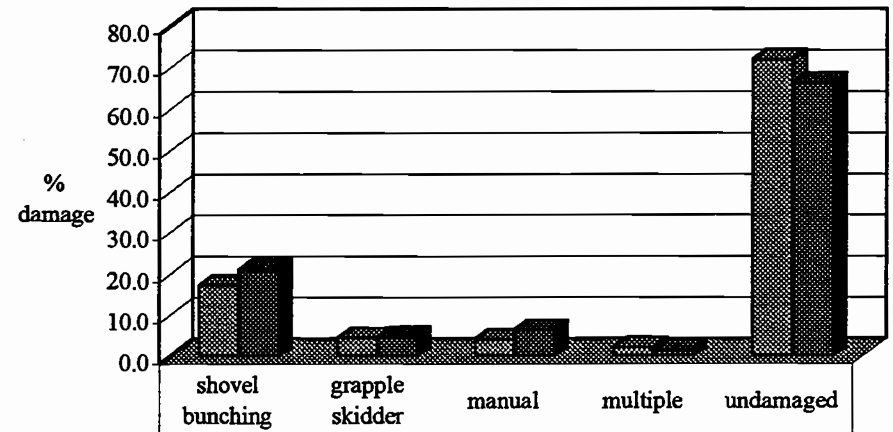
	feller-buncher	grapple skidder	multiple	undamaged
conventional	48.1	6.2	8.2	37.4
designated	47.2	9.0	6.5	37.4

Figure 17. Percent residual stand damage by equipment and layout design, harvest system B (shovel prebunching; partial-tree).



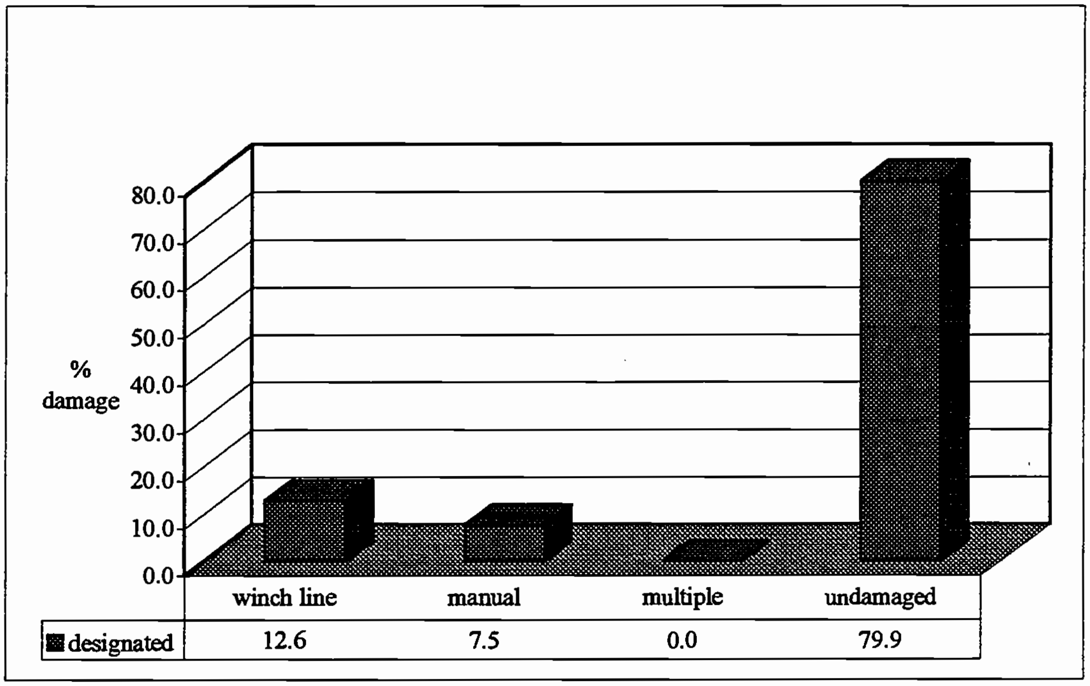
	shovel bunching	grapple	manual felling	multiple	undamaged
conventional	45.1	5.6	0.0	10.0	39.4
designated	29.3	4.1	3.2	5.0	58.4

Figure 18. Percent residual stand damage by equipment and layout design, harvest system C (shovel prebunching; log-length).



	shovel bunching	grapple skidder	manual	multiple	undamaged
conventional	17.2	4.4	4.2	2.1	72.0
designated	21.0	4.7	6.3	1.7	66.3

Figure 19. Percent residual stand damage by equipment for designated layout design[1], harvest system D (winch line).

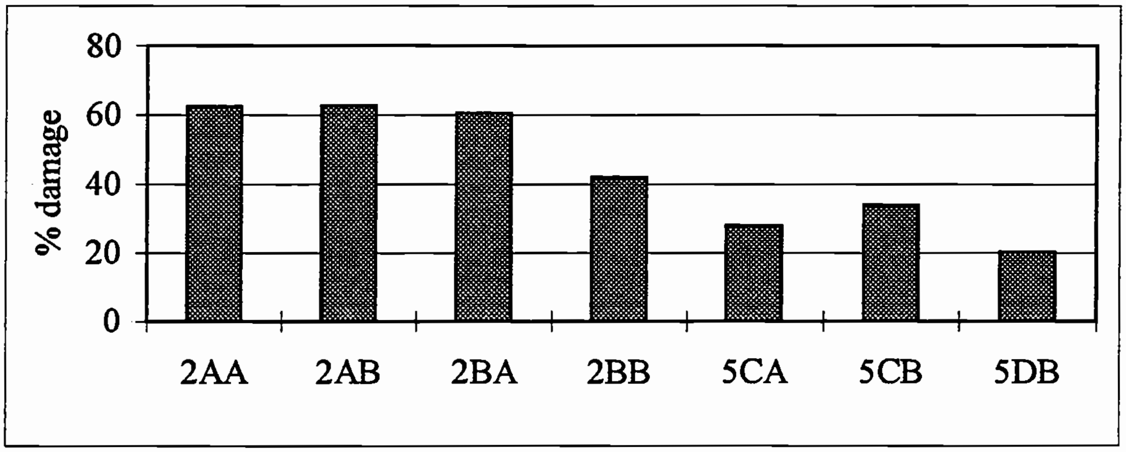


[1]Conventional layout design not included in study due to adverse weather conditions.

7.5.2 *Residual Stand Damage by Harvest System and Layout Design*

The total percent residual stand damage is reported for each harvesting unit in Figure 20 and Table 30. The results are based on the average percent stand damage obtained from individual fixed-radius survey plots.

Figure 20. Total percent residual stand damage by harvest unit[1].



[1]Harvest units are defined as:

- 2AA, feller-buncher, conventional.
- 2AB, feller-buncher, designated.
- 2BA, shovel for prebunching, partial-tree, conventional.
- 2BB, shovel for prebunching, partial-tree, designated.
- 5CA, shovel for prebunching, log-length, conventional.
- 5CB, shovel for prebunching, log-length, designated.
- 5DB, winch line, log-length, designated.

Table 30. Residual stand damage by harvest unit and layout design for individual fixed-radius survey plots.

Harvest Unit	Mean[1]	Std. Error	Minimum[2]	Maximum[2]	Statistical Difference[3]
2AA	62.58	5.50	43.75	93.33	X
2AB	62.62	4.34	44.44	80.00	X
2BA	60.58	7.06	25.00	93.75	X
2BB	41.58	4.49	28.57	69.23	Y
5CA	27.98	2.82	16.67	41.18	Z
5CB	33.74	4.21	16.67	53.85	Y Z
5DB	20.12	4.49	7.69	53.85	Z

[1]Percent of residual stand.

[2]Minimum and maximum mean residual stand damage for individual fixed-radius plots.

[3]Within each harvesting unit, the levels containing X, Y, and Z form a group of means within which there is no statistically significant difference (based on Fisher's LSD).

7.5.3 *Scar Characteristics by Equipment Type*

The average scar area per tree (Figure 21 and Table 31) is reported in 0.1-ft^2.

Figure 21. Average scar area by equipment type for all harvesting units.

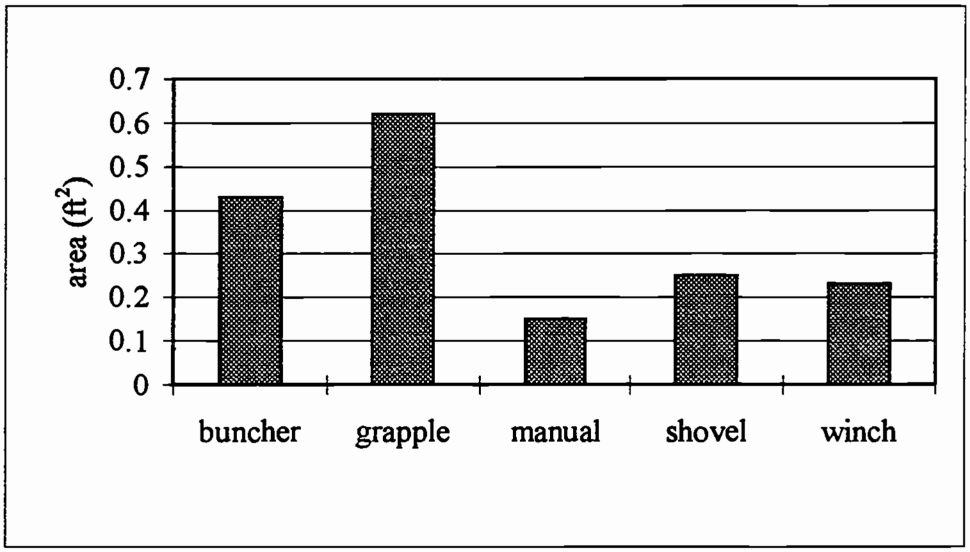


Table 31. Scar area (ft^2) by equipment type for all harvesting units.

Equipment	Mean	Std. Error	Minimum	Maximum	Statistical Difference[1]
Buncher	0.4	0.03	0.1	6.0	Y
Grapple	0.6	0.05	0.1	4.5	Z
Manual	0.2	0.07	0.1	1.0	X
Shovel	0.3	0.03	0.1	2.0	X
Winch	0.2	0.13	0.1	0.7	X Y

[1]For each piece of equipment, the levels containing X, Y, and Z form a group of means within which there is no statistically significant difference (based on Fisher's LSD).

The average scar height (to the nearest 0.5-ft and measures in the center of the scar) is shown in Figure 22 and Table 32.

Figure 22. Average scar height by equipment type for all harvesting units.

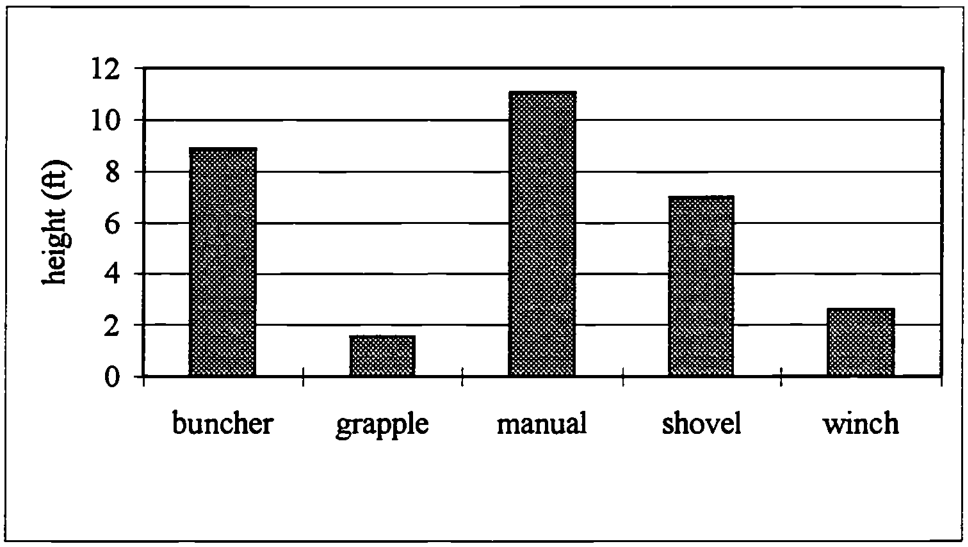


Table 32. Scar height (ft) by equipment type for all harvesting units.

Equipment	Mean	Std. Error	Minimum	Maximum	Statistical Difference[1]
Buncher	8.9	0.40	0.0	45.0	Y
Grapple	1.6	0.68	0.0	12.0	W
Manual	11.1	0.97	0.5	32.0	Z
Shovel	7.0	0.40	0.0	40.0	X
Winch	2.6	1.90	0.5	5.0	W

[1]For each piece of equipment, the levels containing W, X, Y, and Z form a group of means within which there is no statistically significant difference (based on Fisher's LSD).

Figure 23 and Table 33 shows the gouge depth of scars (measured to the nearest cm of wood removed beneath the cambium).

Figure 23. Average scar gouging depth by equipment type for all harvesting units.

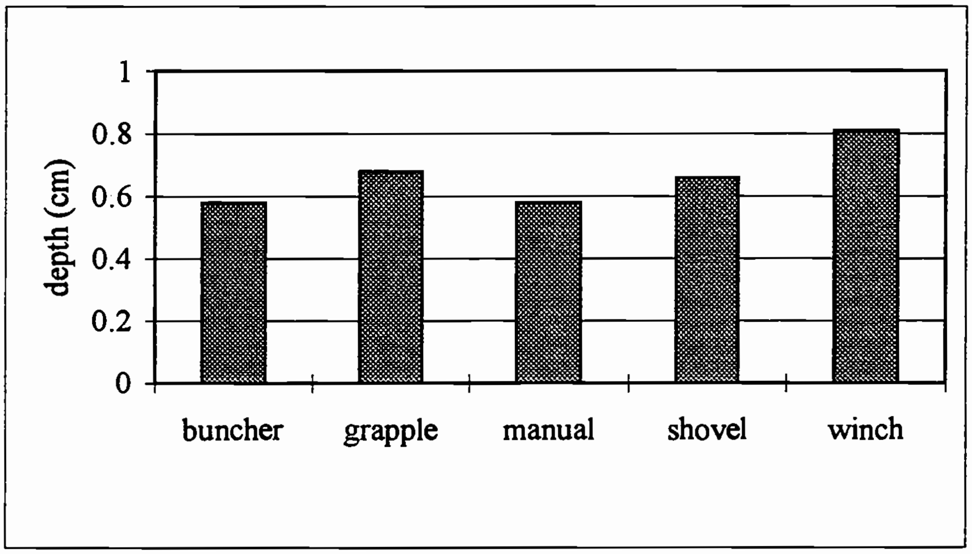


Table 33. Scar gouging depth (cm) by equipment type for all harvesting units.

Equipment	Mean	Std. Error	Minimum	Maximum	Statistical Difference[1]
Buncher	0.6	0.05	0.0	10.0	X
Grapple	0.7	0.09	0.0	5.0	X
Manual	0.6	0.13	0.0	10.0	X
Shovel	0.7	0.05	0.0	10.0	X
Winch	0.8	0.25	0.0	3.0	X

[1]For each piece of equipment, the level containing X forms a group of means within which there is no statistically significant difference (based on Fisher's LSD).

7.5.4 *Scarring Severity of Individual Trees*

Tables 34 and 35 show the average number of scars on an individual tree, as well as the scar area per acre by harvesting units and individual equipment. If only percent stand damage information was presented, the picture would not be complete. Therefore, the concept of a severity level was used to illustrate the true number of scars that each system produced.

Table 34. Severity level (# of scars/tree) by harvesting unit and equipment type.

	2AA	2AB	2BA	2BB	5CA	5CB	5DB
Buncher	2.35	2.45	-------	-------	-------	-------	-------
Grapple	1.23	1.70	1.69	1.90	1.67	1.50	-------
Shovel	-------	-------	2.12	1.96	1.59	1.92	-------
Manual	-------	-------	2.00	1.60	1.97	1.00	1.25
Winch	-------	-------	-------	-------	-------	-------	1.33
TOTAL[1]	2.10	2.29	2.04	1.91	1.62	1.67	1.30

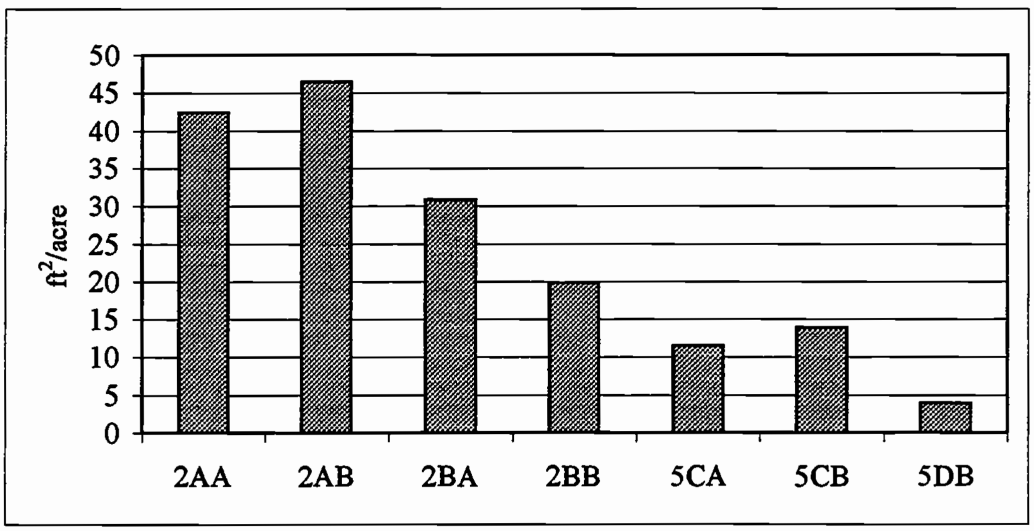
[1]TOTAL severity level for all equipment is the averaged equipment value for an individual harvest unit.

To calculate the scar area per acre, several variables in the stand damage survey were used. From data in Table 34, the average number of scars per damaged tree was calculated, using the total number of scars divided by the total number of damaged trees found in the survey. By multiplying this ratio by the residual tpa, percent damage, and average scar area, the scar area per acre was determined. The scar area for each piece of equipment in the harvest unit was then summed to obtain the total scar area per acre for the individual harvesting units (TOTAL). The equipment and harvesting unit results are shown in Table 35 and the total scar area per acre is illustrated in Figure 24.

Table 35. Scar area (ft^2) per acre by harvesting unit and equipment type.

	2AA	2AB	2BA	2BB	5CA	5CB	5DB
Buncher	36.74	37.13	-------	-------	-------	-------	-------
Grapple	5.69	9.37	6.76	4.93	3.83	3.56	-------
Shovel	-------	-------	23.07	13.69	6.41	9.32	-------
Manual	-------	-------	.99	1.17	1.23	1.03	1.41
Winch	-------	-------	-------	-------	-------	-------	2.52
TOTAL	42.43	46.50	30.82	19.79	11.47	13.91	3.93

Figure 24. Scar area (ft^2) per acre by harvesting unit[1].



[1]Harvest units are defined as:

2AA, feller-buncher, conventional.
2AB, feller-buncher, designated.
2BA, shovel for prebunching, partial-tree, conventional.
2BB, shovel for prebunching, partial-tree, designated.
5CA, shovel for prebunching, log-length, conventional.
5CB, shovel for prebunching, log-length, designated.
5DB, winch line, log-length, designated.

8.0 DISCUSSION

8.1 Harvesting Cost

The two costing scenarios demonstrated harvesting cost differences related to the variability of timber removed from the two harvesting blocks, as well as other harvest unit differences. Total harvesting cost was impacted significantly when the actual volume removed was used in the average piece size calculation. However, due to the limited impacts that different piece sizes had on equipment's TPT, harvest units used a consistent volume for better-cost comparison.

The overall average piece size (131.9 bf/piece) does not differ enough from the individual block calculations to effect the operational aspects of the systems. The same cycle times and equipment costs were used for both scenarios. In the detailed time study, the number of trees, logs, and tops per cycle were recorded. When the multiple linear regression models were determined, load size was not a significant variable in any system but the rubber-tired skidder equipped with a winch line. This skidding cycle was unrelated to load size, but rather to the increased hook time required per log.

8.1.1 *System and Layout Comparison*

With harvest system costs varying +5% to –4% between the conventional and designated layout methods, there is no significant total harvesting cost difference. Layout costs contributed about 1.0 to 0.5% of the total harvesting cost in the designated method, and only 0.5 to 0.1% in the conventional method. Layout time involved with the designated units was greater than for the conventional units, but the impacts on total harvesting cost were minimal.

Layout cost was not the only factor in the overall harvesting cost, with respect to the different layout methods. As harvest unit layout and planning efforts increased the logging pattern changed. Skid trails were located, cut, and cleared before the remaining stands were felled. These added tasks that generated a well-organized skidding pattern but did not cause a detectable difference between harvesting unit cost among layout methods.

The main differences in cost were among the different harvesting systems. Looking at Scenario I only, the harvest systems are ranked according to cost per MBF and their percent increases are shown in Table 36. Based on the difference in total harvesting cost, there appear to be two cost groupings. The first is harvest units 2AA, 2AB, and 5DB, and the second is units 2BA, 2BB, 5CA,and 5CB.

Table 36. Harvest system cost compression and ranking.

Harvest Unit	Cost Rank[2]	Total Harvesting Cost ($/MBF)	% Cost Difference Between Layout A & B	% Cost Difference from Baseline System (2AB)[1]
2AA	2	71.21	-5.11	+5.11
2AB	1	67.75		Base Line (0)
2BA	4	84.48	+4.18	+24.69
2BB	5	88.01		+29.90
5CA	6	91.42	+1.36	+34.94
5CB	7	92.66		+36.77
5DB	3	71.79	N/A	+5.96

[1]Lowest total harvesting cost was used to determine the baseline harvest unit.
[2]Order from low to high harvesting costs (1-7).

With the range of high to low variable and fixed ownership and operating cost of the harvest systems, equipment production is important. Table 37 provides a contrast between the harvest systems, cost and production.

Table 37. Total ownership and operating cost per hour and average hourly production (MBF).

Harvest Units	Total Ownership and Operating Cost ($/hour)	Total Harvesting Cost ($/MBF)	Average Production (MBF/hour)	% Production Difference from Baseline System (2AB)[1]
2AA	474.39	71.21	6.66	-4.86
2AB		67.75	7.00	Baseline (0)
2BA	508.39	84.48	6.02	-14.00
2BB		88.01	5.78	-17.43
5CA	528.93	91.42	5.79	-17.29
5CB		92.66	5.71	-18.43
5DB	282.28	71.79	3.93	-43.86%

[1]The highest average production was used to determine the baseline value.

The production of an individual harvesting system has a dramatic effect on the total harvesting cost; this cannot be predicted by looking at production alone. Harvest system 5DB (winch line) was the lowest volume-producing system at –43.86% from baseline system 2AB (feller-buncher). When looking at the hourly ownership and operating cost, system 5DB was the lowest as well. The combination of lower equipment and harvesting costs also produced a low production rate, which may not be ideal. If you look at a system with high equipment costs, but relatively low total harvest costs (e.g. 2AA and 2AB) you are getting much higher rates of production, despite expensive equipment. There is a production cost trade-off between the lower and higher costing systems. If production needs to be maintained while keeping harvesting costs low, modifications need to be made to utilize more of the lower costing equipment. By adding an additional rubber-tired skidders in harvest system 5DB, production would increase and cost should remain low.

8.1.2 *Equipment Utilization and Interactions*

The ownership and operating costs of the more mechanized equipment (feller-buncher and stroke-boom delimber) were considerably higher than for the less mechanized equipment (manual felling and grapple or winch-line skidders). With operating costs over $100/hour, these pieces of equipment needed high production rates to lower harvesting costs. In order to keep production at its maximum, utilization of the different pieces of equipment were essential. Downtime and adverse equipment interactions began to make more of an impact regardless of equipment ownership and operating cost, but as equipment cost increased, so did the impacts.

Equipment needs to work effectively in a harvesting system. If one piece of equipment is absent, the operation should not suffer a drastic production loss, but should function for a limited time. In addition, if a piece of equipment outproduces the one feeding it, delay and downtime will result without proper planning.

Both of these situations commonly occurred during the course of the study. In harvest systems 2AA and 2AB, the feller-buncher and grapple skidder worked side-by-side. If the feller-buncher experienced a breakdown, a double delay resulted. The delimber and loader also remained idle during these delays unless there was a stockpile of logs. Mechanical delays were not the only problems encountered with this side-by-side operation. The grapple skidder consistently outperformed the feller-buncher on a volume-per-hour basis. This created numerous short-term delays within each cycle. The effective hour for the grapple skidder was reduced by 58% in harvest system 2AB (feller-buncher; designated), in a worst-case scenario.

Problems with interactions were reduced when equipment worked more independently. Manual felling allowed cutters to work well ahead of the primary skidding operations. Skid trails were cleared before the harvesting began off the skid trails. This allowed for more equipment mobility and gave increased options for skidding and prebunching. While delays still occurred, the independent equipment delays were not as strongly related to harvest system interactions as were the side-by-side operations.

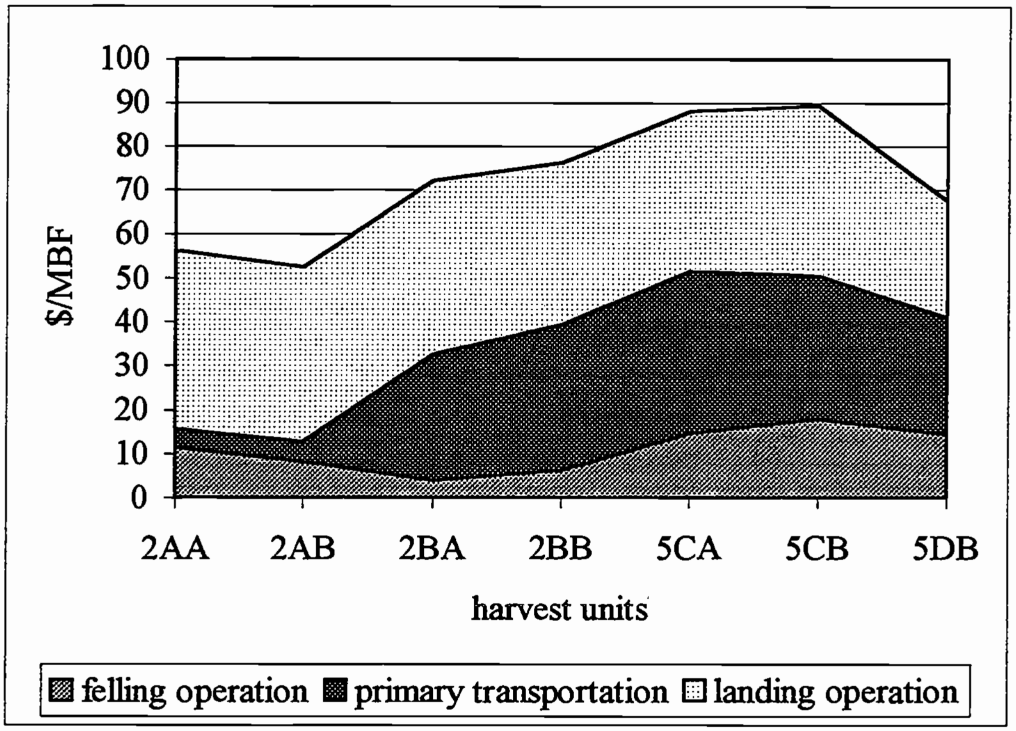
At the centralized and roadside landings, similar results were found for both design types. Except for variations in skidding distances, system configurations, and landing sizes, there were no significant differences between landing activities. Loading and chasing activities increased slightly when roadside landings were used. With an increase in the number of pieces, log handling, and shorter skidding cycles (i.e., the skidder brought logs to the landing more frequently), the loader and chaser were utilized more.

One adverse effect was seen with the roadside landings. When a log truck was present, the loader had to clear the chute and also load the trucks. This congestion increased delay time for skidders waiting to enter the landing area. Due to the smaller size and limited entry to the roadside landings, the skidder could not maneuver. This delay occurred after several turns were dropped off, and persisted until the log drop area was cleared. This delay would become more significant if the number of truckloads per day were to increase. At centralized landings, the stroke-boom delimber cleared the chute and predecked logs while the loader was busy.

8.1.3 *Cost Comparison between Main Harvesting Components*

Three main cost components were broken out of the total harvesting cost: felling operations, primary transportation, and landing operations. Felling operations included the feller-buncher and manual felling. Primary transportation included prebunching with the shovel and skidding. Because the use of the swing-boom grapple skidder was minimal in harvest systems A and B, its cost was not included in the primary transportation. Finally, the landing operations included the stroke-boom delimber (used either to process logs or in place of the log loader for clearing the chute and decking), log loader, and chaser. Figure 25 illustrates the change in component costs between the harvesting units.

Figure 25. Main harvesting component costs for felling operation, primary transportation, and landing operations.



Although the proportion of harvesting cost attributed to the landing operations was similar among the units (except for 5DB), the felling operation and primary transportation costs varied. Harvest unit 5DB (winch line) did not use the stroke-boom delimber, so landing operation costs were lower. When the feller-buncher was used in the felling operations (harvest units 2AA and 2AB), the costs were higher than for manual felling of partial trees (units 2BA and 2BB). Felling costs increased (over those in the partial-tree system) because the trees were processed into log lengths in Block 5. Primary transportation caused the most offset in the overall cost. When the shovel prebunched logs and skidded them to the landing with a grapple skidder (harvest units 2BA –5CB) or the rubber-tired skidder equipped with a winch line was used (5DB), primary transportation costs increased substantially. This increase resulted from higher or equal equipment costs with a decrease in overall production.

8.2 Stand Damage

8.2.1 *System and Layout Comparison*

Several factors affected the amount of residual stand damage: equipment, layout design, and piece size. In this section, possible reasons and relationships contributing to stand damage are discussed and overall stand damage for each harvesting unit is compared.

Equipment type and size, movement in the stand, and pieces handled all contributed to the level of stand damage. In all cases, most stand damage was caused by the primary log mover, which was the piece of equipment that handled or moved the largest quantity of material or pieces. In the case of the feller-buncher, the primary log mover of harvest system 2AA and 2AB, trees were felled and bunched along skid trails. As a result, the feller-buncher handled the least number of pieces per turn while the grapple skidder had an average load of 6 trees per turn. This also was true for the prebunching in systems 2BA, 2BB, 5CA, and 5CB. Manual felling handled each tree individually and logs were bucked into partial-tree lengths and/or log lengths. Additional factors, such as equipment size and corresponding movement through the stand, increased the incidence and severity of residual damage. In system 5DB the rubber-tired skidder equipped with a winch line was the primary log mover. Based on the number of pieces handled, equipment size and movement through the stand, the skidder outweighed the manual felling as the primary log mover.

The primary log mover was the largest piece of equipment, and because it visited every tree in the stand, it was one of the most mobile harvesting components. Larger sizes, greater log movement, and smaller turn sizes (more cycles) increased the equipment's contribution to overall residual stand damage.

The second factor, layout design, had only minimal influence on stand damage in the majority of harvesting units. While an increased level of harvest planning and layout has been shown in the literature review to significantly reduce the amount of residual stand damage in the past, this was not the case in the current study. However, because of several conflicts in the proper implementation of the designated layout units and an increased level of harvest planning in the conventional layout, a true comparison was not possible. In the case of harvesting units 2AA and 2AB (feller-buncher), skid trails were not located in the conventional units while the designated skid trails in the unit 2AB were not used. As a result, the outcomes of the stand damage surveys were almost identical. Likewise, in harvest units 5CA and 5CB (shovel prebunching; log-length), although the designated skid trails were utilized properly in the designated layout unit, a similar skidding pattern emerged from additional planning in the conventional layout unit because of the choice made by the contract logger.

The only true layout comparison was between harvest units 2BA and 2BB (shovel prebunching; partial-tree). In this case, designated trails were located and cleared before felling the remaining stand. The conventional layout had minimal planning and no skid trails were located prior to felling. A comparable and measurable difference was seen between the two methods. Most of the reduction in stand damage was due to the primary log mover, the shovel, for prebunching. A 16.8% drop in residual stand damage by the shovel was observed while damage from all other equipment in the system remained the same. Because of the lack of predesignated skid trails and directional felling, partial trees and logs were crisscrossed in the stand. The shovel could not effectively extract and bunch logs to skid trails. Excessive log movement and swinging of awkward turns caused a higher incidence of residual stand damage.

Harvest system 5DB (rubber-tired skidder equipped with a winch line) only had the designated layout method. Due to adverse weather conditions harvest system 5DA, the conventional method, used a different system to remove the standing and downed timber, and data was not gathered for comparison.

The final factor, piece size, affected residual stand damage. As the piece size (length) was reduced from whole-tree to log-length, residual stand damage decreased. However, several confounding variables limited this comparison. As piece size was reduced, the harvesting system was modified. For example, whole-tree harvesting with the feller-buncher and one of the log-length systems were paired with rubber-tired skidders equipped with winch lines. The only side-by-side comparison was between the partial-tree and log-length methods using the shovel for prebunching (2BA, 2BB, 5CA, and 5CB). In these cases the most noticeable reduction in overall stand damage came from the primary mover as piece size was reduced.

8.2.2 *Scar Characteristics*

Data on scar characteristics demonstrated the type of damage each piece of equipment created. Even though two pieces of equipment may have caused the same percent stand damage, each produced scars with different characteristics.

The grapple skidder caused the largest average scar size. Confined to a narrow trail, the skidder had to maneuver a load of logs around bends and obstacles, and repeated travel over a skid trail continually wounded trees adjacent to the trail. This resulted in a large average scar area of just over 0.6 ft^2. The second largest average scar (0.4 ft^2) was produced by the feller-buncher. The extra force from pushing a tree down through the residual stand caused long, narrow scars of considerable length. The manual felling, shovel, and skidder equipped with a winch produced scar sizes similar to each other (0.2 – 0.3 ft^2). The smaller loads and reduced piece size (log-length) contributed to the lower scar area in the unit with a winch line skidder, instead of a grapple skidder.

Scar height was an excellent indicator of the effectiveness of preharvest tree protection from grapple skidders and skidders equipped with winch lines. With average scar heights 1.6 and 2.6 ft, respectively, the grapple and winch line damage was well below that of the feller-buncher, manual felling, and shovel (8.9, 11.1. and 7.0 ft, respectively). At these heights pre-treating trees with artificial protection is not feasible.

Scar depth ranged from 0.6 – 0.8 cm, and showed very little variability among the different pieces of equipment.

8.2.3 *Individual Tree Damage and Severity*

Although percent residual stand damage measured the number of trees wounded during the logging operation, it did not provide information on an individual-tree basis. Table 38 shows the stand damage severity level (number of scars per tree).

Table 38. Percent difference of stand damage severity level by harvesting unit.

Harvesting Unit	Total Scars Per Tree	Percent Decrease from Baseline[1]
2AA	2.10	-8.30
2AB	2.29	Baseline (0.0)
2BA	2.04	-10.92
2BB	1.91	-16.59
5CA	1.62	-29.26
5CB	1.67	-27.07
5DB	1.30	-43.23

[1]The highest number of scars per tree was used to determine the baseline harvest unit.

The number of scars per tree followed the same trend observed in percent residual stand damage. As equipment and piece sizes were reduced, the number of scars per tree decreased. The percent decrease from the baseline (harvest unit 2AB, feller-buncher; designated) paired with the percent stand damage magnified that difference.

Determining the number of scars per harvest block was the intermediate step in determining total scar area per acre (Table 39). This provided the best representation of overall stand damage. By incorporating percent residual stand damage, average number of scars per tree, average scar area, and residual tpa all values were summed into a single measure of stand damage.

Table 39. Average total scar area per acre and percent by harvesting unit.

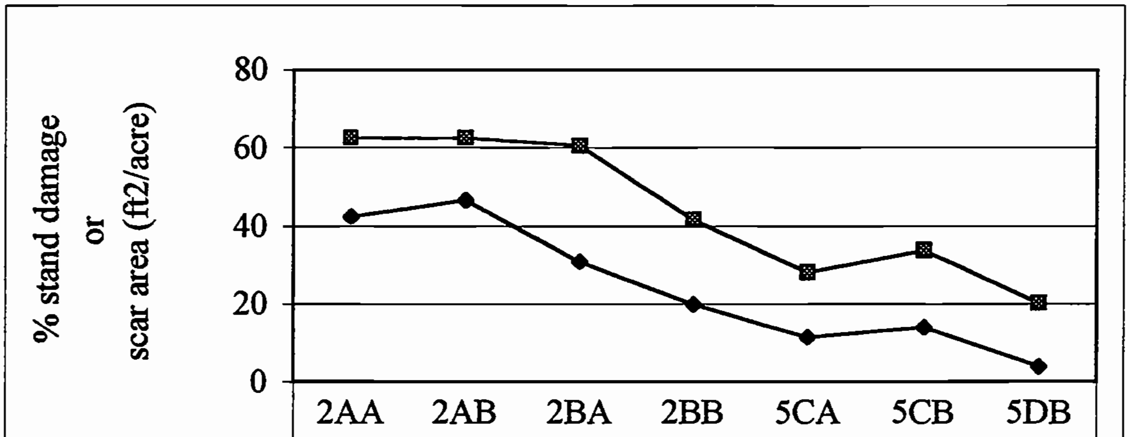
Harvesting Unit	Average Scar Area Per Acre (Ft^2)	Percent Decrease from Baseline[1]
2AA	42.43	-8.75
2AB	46.50	Baseline (0.0)
2BA	30.82	-33.72
2BB	19.79	-57.44
5CA	11.46	-75.35
5CB	13.91	-70.09
5DB	3.93	-91.55

[1]The highest total scar area per acre was used to determine the baseline harvest unit.

When the percent residual stand damage was compared with the average scar area per acre the influence of harvesting unit was similar (Figure 26). Fluctuations in the average scar area per acre corresponded with changes in percent stand damage.

While the trends between the two were similar, their magnitudes differed. A 91.55% decrease from the baseline was observed from the highest to lowest damage value (Table 39). Harvest units 2AA and 2AB (feller-buncher) had over 10 times the amount of scar area per acre than did unit 5DB (rubber-tired skidder equipped with a winch line; designated).

Figure 26. Comparison of percent residual stand damage and scar area (ft^2 per acre).[1]



	2AA	2AB	2BA	2BB	5CA	5CB	5DB
stand damage	62.58	62.62	60.58	41.58	27.98	33.74	20.12
scar area/acre	42.43	46.50	30.82	19.79	11.46	13.91	3.93

[1]Harvest units are defined as:

2AA, feller-buncher, conventional.
2AB, feller-buncher, designated.
2BA, shovel for prebunching, partial tree, conventional.
2BB, shovel for prebunching, partial tree, designated.
5CA, shovel for prebunching, log length, conventional.
5CB, shovel for prebunching, log length, designated.
5DB, winch line, log length, designated.

8.3 Harvest Unit Layout and Design

Increased layout time had little impact on the overall harvesting cost. Due to the ease of layout, proper implementation took minimal time. Designated skid trail location was the only varying factor between the two methods.

Reduction in stand damage and severity were significantly affected by log length, which was specific to the harvest system design. The main contributor to stand damage was the combination of mechanical felling and bunching. Although manual felling alone produced minimal stand damage, it was combined with prebunching to form a single felling and bunching damage value (for comparison to the feller-buncher). The resultant damage levels were 48.1, 47.2, 45.1, 32.5, 21.4, and 27.3% (harvest systems 2AA, 2AB, 2BA, 2BB, 5CA, and 5CB,respectively). Residual stand damage decreased as the log length was reduced in the felling and bunching operations. Stand damage caused by the grapple skidder was similar in the three systems.

To reduce stand damage, rub trees and tree protection were required on all designated layout designs. Rub trees were marked along designated skid trails and prevented damage to residual trees. Corrugated plastic culvert pipe (approximately 36 inches in diameter x 4 ft long) was cut into three sections lengthwise. These sections were to be strapped onto residual trees along skid trails or where needed to protect the lower bole of the tree. In the current study, however, these proven measures of damage prevention (Aho et al. 1983a. 1983b) were not used by the equipment operators. The rub trees marked along the skid trails prevented damage, however, when designated skid trails were not adhered to the trees became useless. The plastic tree protectors when properly placed on a residual tree prevented or minimized tree damage. However, the equipment operators were unwilling to use the tree protection. In total, over 10 artificial tree protectors were available for use. They were designed to be lightweight, mobile, and easy to install. The average installation only took about 3 minutes from equipment cab to tree and back. The unwillingness to use these barriers came from several preconceived ideas that they did not work, resistance to new ideas and change, and they were a waste of time and unimportant to use. It should be noted however, that the proper implementation of the rub tree and tree barriers would not have reduced the overall stand damage in most harvesting units. There may have been a more significant reduction in total scar area per acre, but not a very significant drop in percent stand damage because of the average scar height caused by the primary log mover.

The one harvest unit that would have greatly benefited from the use of tree protection was unit 5DB (winch line). Because the majority of damage came from the rubber-tired skidder equipped with a winch line and operator-set chokers, the operators could easily have moved and placed the plastic culverts where needed as they went from trail to trail.

Landing design had little effect on the production in each system. By the end of harvesting, Block 2 had two centralized landings and Block 5 had six roadside landings. This was equal to 0.66 acres of total landing area in Block 2 and 1.05 acres (not including road surface) in Block 5. The Warm Springs forest practice rules state that landing size (approximately 120 ft x 50 ft) will be kept to a maximum of 0.14 acres per 10 acres harvested. Based on this requirement, the total landing size per 60-acre block should have been 0.84 acres. The centralized landings were 21.34% below this amount but the roadside landings exceeded this by 25.0%. These two landing designs did, however, work effectively for each harvesting system. Although there was more impacted area in Block 5, the skidding distances were much shorter, resulting in faster turn times that increased production (pieces/hour).

A final issue related to unit layout was skid trail spacing. The Warm Springs forest practice rules state that skid trails will average 120-ft apart. The average skid trail spacing for harvest systems A, B, and C was approximately 80-ft. This closer spacing was needed because of the limited reach (maximum 30-ft) of the feller-buncher and shovel for prebunching. Harvest system D utilized a winch line, was capable of meeting and exceeding this requirement. With an average pulling distance of 26.5-ft, logs up to 60 feet were easily reached using an average skid trail spacing of 120-ft.

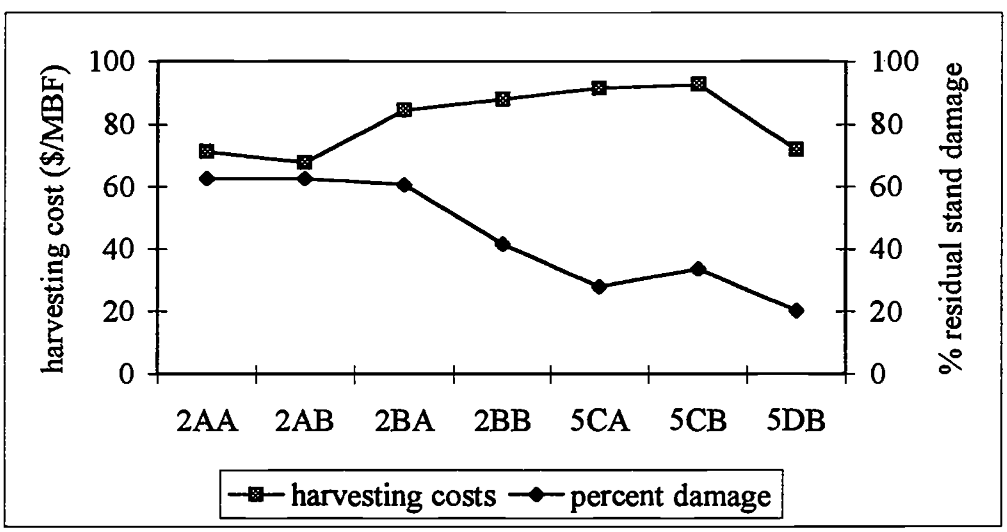
8.4 Harvesting Cost and Stand Damage Matrix

The final objective of this study was to derive a harvesting cost and stand damage matrix. Based on the total harvesting cost in Scenario I and the total percent residual damage for each block, a matrix was developed (Figure 27 and 28).

Figure 27. Harvesting cost and stand damage matrix.

	Harvest System 2A	Harvest System 2B	Harvest System 5C	Harvest System 5D
Layout A	71.20 $/MBF 62.58 %	84.49 $/MBF 60.58 %	91.40 $/MBF 27.98 %	N/A
Layout B	67.77 $/MBF 62.62 %	88.01 $/MBF 41.58 %	92.68 $/MBF 33.74 %	71.79 $/MBF 20.12 %

Figure 28. Harvesting cost and percent stand damage, comparison by block.



In addition, a matrix was formed that represented total harvesting cost and scar area per acre (Figure 29). Including the scar area data provided a more comprehensive measure of stand damage.

Figure 29. Harvesting cost and scar area per acre (ft^2) matrix.

	Harvest System 2A	Harvest System 2B	Harvest System 5C	Harvest System 5D
Layout A	71.20 $/MBF 42.43 ft^2	84.49 $/MBF 30.82 ft^2	91.40 $/MBF 11.46 ft^2	N/A
Layout B	67.77 $/MBF 46.50 ft^2	88.01 $/MBF 19.79 ft^2	92.68 $/MBF 13.91 ft^2	71.79 $/MBF 3.93 ft^2

8.5 Other Study Issues

Several issues that arose during the study and data analysis are addressed in this section: ownership and operating cost calculations and logging contractor experience.

An estimated new-purchase price was needed for all equipment the operation. A Caterpillar sales representative from Pape Bros., Inc. of Eugene, Oregon, was contacted to determine the new purchase price of the harvesting equipment (Scharlund 1997). The assumption often made is that a logging company owner will cost out their operation for future purchases of new equipment. However, in some cases the owner might be purchasing used equipment that costs considerably less to own and operate. If used equipment cost and expenses were considered in the cost calculations, a lower ownership cost but and increased operating hourly rate would result. However, the decreased ownership costs could far outweigh the increase in operating cost caused by higher equipment maintenance.

It was not immediately apparent, that the use of higher-cost equipment (e.g. stroke-boom delimber) among the four systems was unbalanced. Table 40 presents a comparison of the two different costing methods using log volumes from Scenario I. Full reports on hourly operating and ownership costs are found in Appendices D and E. Used-equipment costs were averaging using a range of prices from a used-heavy equipment publication (Pierce 1997).

Table 40. Total harvesting cost with new and used equipment.

Harvest Unit	Total Harvesting Cost ($/MBF)		% Change
	New	USED	
2AA	71.20	52.69	-25.6
2AB	67.77	50.78	-25.1
2BA	84.49	62.50	-26.0
2BB	88.01	65.04	-26.1
5CA	91.40	69.53	-23.9
5CB	92.68	71.78	-22.6
5DB	71.79	62.83	-12.5

The amount in savings was not uniform in the final harvesting cost. The first three harvest systems (six harvest units) had a relatively equal drop in harvesting cost, but unit 5DB (winch line) did not use the more expensive equipment (feller-buncher, shovel, and stroke-boom delimber). Ownership and operating costs of the new equipment was more than three greater than used equipment. Even though used equipment had a shorter life and higher maintenance, the hourly ownership and operating cost was greatly reduced.

The use of new or used equipment cost was discussed as it related to the differing results produced from the two costing assumptions. It was intended to show the potential extremes between used and new equipment. For the current study analysis, however, a consistent new-equipment costing approach was taken.

Table 41 describes the logging crew experience for total time spent in timber work (Garrett, 1996).

Table 41. Logging crew experience in years.

Equipment or Job	Years of Experience	Type of Experience
Foreman	22	50% cable-yarding, 50% ground based
Feller-buncher	32	60% ground-based, 20% faller, 20% cable
Shovel	32	60% ground-based, 20% faller, 20% cable
Log Loader	26	mostly operated in "big wood"
Grapple Skidder	9	100% ground-based
Swing-boom Skidder	8	100% ground-based
Chaser	0.5	100% ground-based
Fallers	10[1]	variety of timber types

[1]Eight fallers had an average experience of 10 years.

8.6 Suggestions for Future Logging Operations

Based on conclusions from past studies, the following general suggestions are made for thinning noble fir stands:

1. Process trees by hand, keeping log lengths to a minimum.
2. Use equipment compatible with the type of timber and silvicultural prescription.
3. Properly install and utilize designated skid trails.
4. Minimize the amount of equipment operating in the stand.
5. Implement a logger incentive program.
6. Set and enforce tolerable damage levels.
7. Educate operators on damage-reducing techniques.

Manual felling and processing trees log-length in the stand was shown to significantly reduce the level of stand damage compared to higher levels of harvesting mechanization. Larger pieces of equipment either needed to be eliminated from the stand or confined to designated skid trails. The large-sized undercarriages on the feller-buncher and shovel for prebunching were too large for proper mobility within the stand. Attempts to move off the skid trail and into the stand caused numerous scars by the equipment's large mass and wide swinging and turning radius. It is also important to note that the felling head on the feller-buncher had very limited directional felling capabilities. Once a tree had been severed from the stump, the machine had very little control over its falling path. A falling head with a larger grappling device and improved directional felling capabilities would have reduced the level of stand damage caused by the feller-buncher.

Proper use of designated skid trails would have greatly enhanced the overall design effect. Vehicles that frequently left the skid trails injured roadside and residual trees. In addition, designated skid trials needed appropriate spacing for each type of equipment (skid trails in this study ranged from 60-150 ft apart). Likewise, with every equipment entry into the stand came an increased chance of stand damage. Limiting the amount of equipment through efficient layout and payload maximization would have reduced the number of trips into the stand.

The final three suggestions came from the administrative level. Incentive programs, logger education, and fines and penalties are all ways to reduce the amount of stand damage. A combination of the three is the most complex approach, but assigns responsibility to all parties. First, both loggers and landowners must be educated on the importance and methods of stand damage reduction. The next step would be to impose a range or damage level that is tolerable and must be met. If this level were exceeded a fine or penalty would be incurred by the operator. Moreover, if stand damage was at or below the specified level the operator would receive an incentive or bonus. This would be most critical because the future economic losses or gains are affected by residual stand damage.

Other topics that have been researched in past studies should be utilized as well. As demonstrated in previous studies, directional felling techniques and tree protection should be used in all thinning applications. Directional felling helps to align trees and logs for easier extraction and less log handling. Tree protection deveices (e.g. plastic culvert strips) minimizes stand damage where it is highest in concentration (i.e. along skid trails). Among the four harvesting systems, the feller-buncher or shovel for prebunching caused most of the damage located above the height of a plastic tree barriers (approximately 5 ft). This would suggest that if tree barriers were used properly, the majority of stand damage would then occur during the felling and bunching portion of the operation. Furthermore, in this study, manual felling had the lowest severity and frequency of damage of any piece of equipment. Therefore, from the outcome of this study, it is recommended that a harvest system include the following for thinning in noble fir stands:

1. Premark designated skid trails.
2. Manually fell and clear roads before harvesting the remaining stand.
3. Manually fell remaining timber to trails using directional felling techniques.
4. Limb (three sides) and buck trees into log-length segments prior to skidding.
5. Use rub trees or artificial tree protection along trails, landings, and high-use areas.
6. Confine equipment use to designated skid trails spaced at least 120 ft apart.

This list implies that ground skidding equipment is used with a winch line capable of pulling line to the logs, winching them from the stand to the roads, and skidding logs to the landing.

If systems with more mechanization are used, an increased level of caution needs to be taken. Larger more powerful machines need to work slower and with more care. To minimize stand damage, residual trees need to be avoided. Increased levels of planning that would designate skid trails as well as a proficient-felling pattern are essential.

8.7 *Opportunities for Future Research*

This study was Phase III of a long-term noble fir project. A synthesis of information from all three phases would demonstrate the effects of using different harvesting systems in these stands. It would include data on the growth and yield of the thinned stands, as well as the effects of *Heterobasidion annosum* on decay and volume loss. If residual stand damage degraded the future value of timber, there could be a benefit in damage reduction. From the data collected in these three phases, future gains in timber volume and value can be projected.

Another aspect of this project that was not fully investigated was the cost associated with proven stand damage-reducing techniques. The debates on the use or requirement will continue as more stands are thinned before final harvest. Associated costs need to be addressed. Careful planning and use of these techniques does reduce injury to crop trees. Residual stand damage, production, and harvesting costs are effected by their implementation. However, the costs and time involved in application are still not fully understood.

Finally, a cut-to-length system was not included in this study. The harvesting cost and residual stand damage for this system has been researched, but not extensively in larger timber. Also, the advantages of using a felling head that has improved directional felling and bunching abilities should be investigated.

9.0 CONCLUSION

This project investigated four ground-based harvesting systems in high elevation noble fir stands on the Warm Springs Indian Reservation in the northern Oregon Cascades. Residual stand damage and harvesting costs were determined for each harvesting system. The harvesting systems were:

A. Feller-buncher → Grapple skidder → Delimber
B. Manual felling → Shovel, prebunching → Grapple skidder→ Delimber
C. Manual felling, limbing, bucking → Shovel, prebunching → Grapple skidder
D. Manual felling, limbing, bucking → Rubber-tires skidder with winch line

Trees were processed into three different lengths depending on the system. System A was whole-tree length, system B had a partial -tree method (bottom log bucked), and systems C and D were processed log-length. In addition, two layout methods were used in each system. A conventional or logger-choice method and a designated method to reduce stand damage were compared in each harvesting system.

The study was designed to determine the level of stand damage and harvesting costs incurred by each system and layout method. A comparison of the four harvesting systems showed that log length, equipment compatibility, and planning affect the amount of residual stand damage and total harvesting costs. Costs for the four systems ranged from \$67.77/MBF - \$92.68/MBF, with residual stand damage ranging from 20.12 - 62.62%.

Future harvesting of the noble fir stands needs to proceed with an increased level of planning and sale administration. In addition, the importance of reducing stand damage needs to be stressed to both the landowner and logging contractors.

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APPENDICES

Appendix A Detailed Time Study and Activity Sampling Variables

A.1 Feller-buncher

Dependent Variables:

Moving in stand	**Begins** when forward or backward motion starts, **ends** when movement stops.
Felling cycle	**Begins** when movement stops or when the felling head starts to swing towards a new tree, **ends** when the grapple arms are opened releasing the tree.
Bunching	Includes any moving or positioning of logs for the purpose of bunching along the designated roads.
Brushing	Includes the removal of saplings and brush and the felling of unmerchantable trees.
Delays	Any delay that occurs within the cycle (greater than 10 seconds).

Independent Variables:

Treatment area	Location of turn with respect to harvest blocks.
DBH	Diameter at breast height, measured to the nearest inch.
Number of trees	Number of tree the processing head accumulated or cut.

A.2 Grapple skidder

Dependent Variables:

Travel empty	**Begins** when skidder starts to travel empty from the landing to the stand, **ends** when forward motion stops so that maneuvering or loading can begin.
Positioning	**Begins** at the end of travel empty, **ends** when loading grapple activities start.
Loading	**Begins** at the end of positioning, **ends** when the skidder starts to move with a bunch in the grapple.
Reposition	**Begins** at the end of loading, **ends** when forward motion stops and loading re-commences.
Travel loaded	**Begins** at the end of loading when a full load has been accumulated, **ends** when skidder enters landing.
Unload	**Begins** at the end of travel loaded, **ends** when skidder starts moving again so that travel empty may begin.
Accumulate	Any time spent accumulating scattered logs together for a load.
Delays	Any delays that occur within the cycle (greater than 10 seconds).

Independent Variables:

Treatment area	Location of turn with respect to harvest blocks.
Distance traveled	One way skidding distance measured to the nearest 5 feet.
Number of trees/cycle	any piece greater than 40 feet in length, one bucked end.
Number of logs/cycle	any piece approximately 40 feet in length with bucked ends.
Number of tops/cycle	any piece less than 40 feet in length, one bucked end.

A.3 Manual Felling

Dependent Variables:

Travel	**Begins** when bucking or limbing is complete, **ends** when felling for the next tree starts.
Felling	**Begins** when chainsaw touches the tree, **ends** when tree hits the ground.
Measure and limb	**Begins** when tree hits the ground, **ends** when bucking cut starts.
Buck	**Begins** (usually after limb and measure) when chainsaw begins cutting a horizontal cross section of the main stem, **ends** when travel or limb and measure begin.
Low stumping	Any time spent low-cutting stump after felling of tree.
Delays	Any delays that occur within the cycle (greater than 10 seconds).

Independent Variables:

Treatment area	Location of turn with respect to harvest blocks
Tree #	A designated number that has been prerecorded for dbh, species, and percent ground slope.
Road	An indicator variable that represents the location of the tree with respect to being felled in a designated road or within the stand.
Method	An indicator variable that represents whether a wedge or alternative felling technique was used.

A.4 Shovel

Dependent Variables:

Travel	**Begins** when forward or backward motion start, **ends** when movement stops.
Acquire & swing	**Begins** at end of travel time, **ends** when forward or backward motion starts, or when log is placed in pile.
Reposition	Includes any time spent repositioning a load for swinging to a pile.
Brushing	Includes any time spent move logging slash and unmerchantable timber to retrieve logs or trees.
Delays	Any delay that occurs within the cycle (greater than 10 seconds).

Independent Variables:

Treatment area	Location of turn with respect to harvest blocks.
% Ground slope	Percent ground slope measured to the nearest 1%

A.5 Winch line

Dependent Variables:

Travel empty	**Begins** when skidder leaves landing **or Begins** when end of unhook if no decking, **ends** when skidder slows down on designated skid trail and begins planning for the next turn or leaves skid trail and positions skidder for winching.
Positioning	**Begins** when skidder slows or leaves skid trail and positions skidder for winching, **ends** when operator leaves cab.
Line out	**Begins** when operator leaves cab, **ends** when operator hooks first log in turn.
Hook	**Begins** when operator hooks first log in turn, **ends** when operator moves to next log.
Line out & Hook	These elements repeat until all logs are hooked. Line out continues after the operator or choker-setter leaves the first log and ends when they reach the second log where hooking begins (and so on for the third, fourth, etc.). Line out ends when winching begins inhaul of logs to skidder).
Winching	**Begins** when winching begins (Inhaul of logs to skidder), **ends** when winch line is locked.
Reposition	Is an element that occurs between winching and travel loaded. It includes any movement between the two elements and any additional winching of the line in excess of what was initially pulled out to hook logs.
Travel loaded	**Begins** when winch line is locked, **ends** when skidder stops on landing (or drops winch line).
Unhook	**Begins** when skidder stops on landing (or drops winch line), **ends** when skidder leaves landing.
Delays	Any delays that occur within the cycle (greater than 10 seconds).

Independent Variables:

Treatment area	Location of turn with respect to harvest blocks.
Distance traveled	One-way skidding distance measured to the nearest 5 feet.
Winch line distance	Maximum distance winch line is pulled to a piece for hooking.
Number of trees/turn	Any piece greater than 40 feet in length, one bucked end.
Number of logs/turn	Any piece approximately 40 feet in length, two bucked ends.
Number of tops/turn	Any piece less than 40 feet in length, one bucked end.
Number of chokers/turn	Number of chokers used in a specific turn.
Use of chaser on landing	Indicator variable that represent the presence of the chaser on the landing.

A.6 Activity sample

Loader

Sorting	Sorting of logs and clearing of chute
Loading	Loading of log trucks
W/ch or dl	Delay, waiting on chaser or delimber
Idle	Delay, no activity
Mech.	Delay, mechanical

Delimber

Processing	Limbing and bucking off landing logs
W/ld	Delay, waiting on loader
W/ch	Delay, waiting on chaser
W/sk	Delay, waiting on skidder
Idle	Delay, no activity
Mech.	Delay, mechanical

Skidder

Off landing	Skidder working in the unit of landing
Unloading	Skidder on landing dropping load
Slash	Removing slash from landing
W/dl or ldr	Delay, waiting on delimber or loader
Idle	Delay, no activity
Mech.	Delay, mechanical

Log Truck

Off landing	Log truck not present on landing
On landing	Log truck present on landing
Load ticket	activity involved in the completion of load or scale tickets

Chaser

Chasing	Actively involved in a variety of chasing activities
Idle	No activity, or activity unrelated to chasing

Appendix B PACE Ownership and Operating Cost Equations

Ownership Cost, Equations and Variables:

P = purchase price

S = salvage value

RC = replacement cost of tires, tracks, line, or rigging

N = estimated life of equipment

SH = scheduled hours/year

I = percentage of AAI for interest, taxes, licenses, and insurance

% = borrowing rate + percent of AAI for insurance, licenses, and tax

1. Straight-line Depreciation ($/year)

$$D = \frac{P - S - RC}{N}$$

2. Average Annual Investment ($/year)

$$AAI = \frac{(P - S) \times (N - 1)}{2N} + S$$

3. Interest, Taxes, Insurance ($/year)

$$I = \% \times AAI$$

4. Ownership Cost ($/hour)

$$OwnershipCost = \frac{D + I}{SH}$$

Operating Cost: Equations and Variables:

D= yearly depreciation, determined in Ownership Cost ($/year)

d = percent of depreciation for repairs and maintenance

F = fuel consumption (gallons per hour)

f = fuel cost per gallon

L = percent of fuel consumption for oil and lubricants

l = cost of oil and lubricants per gallon

x_i = cost of major item on machine with a shorter life span than the machine

s_i = life span of the above item (hours)

1. Repair and Maintenance ($/hour)

$$RM = \frac{D \times d}{SH}$$

2. Fuel ($/hour)

$$Fuel = F + f$$

3. Oil and Lubrication ($/hour)

$$OL = F \times L \times l$$

4. Other costs such as lines, tires, tracks, etc.

$$Misc = \sum \frac{x_i}{s_i}$$

5. Total Operating Cost ($/hour)

$$Operating\,Cost = RM + Fuel + OL + Misc$$

Labor Cost, Equations and Variables:

TW = total crew or individual wage

F = percent for fringe benefits

T = travel time per day (hours)

OP = hours worked per day (hour)

SV = percent of direct labor cost for supervision (%)

1. Direct Labor Cost ($/hour)

$$Direct\, LC = TW \times \frac{OP + T}{OP} \times F$$

2. Supervision and Overhead ($/hour)

$$Supervision = Direct\, LC \times SV$$

3. Total Labor Cost

$$Total\, Labor\, Cost = Direct\, LC \times Supervision$$

Appendix C PACE Output, New Equipment Purchase Price

Table 42. Feller-buncher: ownership, operating, and labor cost for NEW equipment price.

Equipment Ownership Cost Inputs		
Delivered equipment cost	$	386,000.00
Minus line and rigging cost	$	0.00
Minus tire and track replacement cost	$	10,000.00
Minus residual (salvage) value	$	57,900.00
Life of equipment (Years)	#	5.00
Number of days worked per year	#	200.00
Number of hours worked per day	#	8.00
Interest Expense	%	10.00
Percent of average annual investment for:		
Taxes, License, Insurance, and Storage	%	3.00
Equipment Operating Cost Inputs		
Percent of equipment depreciation for repairs	%	65.00
Fuel amount (Gallons per hour)	#	4.00
Fuel cost (Per gallon)	$	1.00
Percent of fuel consumption for lubricants	%	7.00
Cost of oil and lubricants (Per gallon)	$	3.50
Cost of lines	$	0.00
Estimated life of lines (Hours)	#	0.00
Cost of rigging	$	35,000.00
Estimated life of rigging (Hours)	#	3,200.00
Cost of tires or tracks	$	10,000.00
Estimate life of tires or tracks (Hours)	#	3,200.00
Summary		
Ownership		
Depreciable value:	$	318,000.00
Equipment depreciation:	$	63,620.00 / Year
Interest expense:	$	25,476.00 / Year
Taxes, license, insurance, and storage:	$	7,642.75 / Year
Annual ownership cost:	$	96,738.80 / Year
Ownership cost (Subtotal)	$	60.46 / Hour
Machine operating		
Repairs and maintenance:	$	25.85 / Hour
Fuel and oil:	$	4.98 / Hour
Lines and rigging:	$	10.94/ Hour
Tires or Tracks	$	3.13 / Hour
Equipment operating cost (Subtotal):	$	44.89 / Hour
Labor:		
Direct labor cost:	$	23.57 / Hour
Supervision and overhead:	$	3.53 / Hour
Labor cost (Subtotal):	$	27.10 / Hour
OWNERSHIP COST	$	60.46 / Hour
OPERATING COST	$	44.89 / Hour
LABOR COST	$	27.10 / Hour
Machine rate (Ownership + Operating + Labor)	$	132.45/ Hour

Table 43. Grapple skidder: ownership, operating, and labor cost for NEW equipment price.

Equipment Ownership Cost Inputs		
Delivered equipment cost	$	170,000.00
Minus line and rigging cost	$	650.00
Minus tire and track replacement cost	$	5,000.00
Minus residual (salvage) value	$	42,500.00
Life of equipment (Years)	#	5.00
Number of days worked per year	#	200.00
Number of hours worked per day	#	8.00
Interest Expense	%	10.00
Percent of average annual investment for:		
Taxes, License, Insurance, and Storage	%	3.00
Equipment Operating Cost Inputs		
Percent of equipment depreciation for repairs	%	65.00
Fuel amount (Gallons per hour)	#	5.00
Fuel cost (Per gallon)	$	1.00
Percent of fuel consumption for lubricants	%	7.00
Cost of oil and lubricants (Per gallon)	$	3.50
Cost of lines	$	150.00
Estimated life of lines (Hours)	#	800.00
Cost of rigging	$	500.00
Estimated life of rigging (Hours)	#	1,600.00
Cost of tires or tracks	$	5,000.00
Estimate life of tires or tracks (Hours)	#	3,200.00
Summary		
Ownership		
Depreciable value:	$	121,850.00 / Year
Equipment depreciation:	$	24,370.00 / Yeas
Interest expense:	$	11,900.00 / Year
Taxes, license, insurance, and storage:	$	3,570.00 / Year
Annual ownership cost:	$	39,840.00 / Year
Ownership cost (Subtotal)	$	24.90 / Hour
Machine operating		
Repairs and maintenance:	$	9.90 / Hour
Fuel and oil:	$	6.22 / Hour
Lines and rigging:	$	0.50 / Hour
Tires or Tracks	$	1.56 / Hour
Equipment operating cost (Subtotal):	$	18.19 / Hour
Labor:		
Direct labor cost:	$	17.01 / Hour
Supervision and overhead:	$	2.55 / Hour
Labor cost (Subtotal):	$	19.56 / Hour
OWNERSHIP COST	$	24.90 / Hour
OPERATING COST	$	18.19 / Hour
LABOR COST	$	19.56 / Hour
Machine rate (Ownership + Operating + Labor)	$	62.65 / Hour

Table 44. Swing-boom skidder: ownership, operating, and labor cost for NEW equipment price.

Equipment Ownership Cost Inputs		
Delivered equipment cost	$	150,000.00
Minus line and rigging cost	$	650.00
Minus tire and track replacement cost	$	5,000.00
Minus residual (salvage) value	$	37,500.00
Life of equipment (Years)	#	5.00
Number of days worked per year	#	200.00
Number of hours worked per day	#	8.00
Interest Expense	%	10.00
Percent of average annual investment for:		
Taxes, License, Insurance, and Storage	%	3.00
Equipment Operating Cost Inputs		
Percent of equipment depreciation for repairs	%	65.00
Fuel amount (Gallons per hour)	#	4.00
Fuel cost (Per gallon)	$	1.00
Percent of fuel consumption for lubricants	%	7.00
Cost of oil and lubricants (Per gallon)	$	3.50
Cost of lines	$	150.00
Estimated life of lines (Hours)	#	800.00
Cost of rigging	$	500.00
Estimated life of rigging (Hours)	#	1,600.00
Cost of tires or tracks	$	5,000.00
Estimate life of tires or tracks (Hours)	#	3,200.00
Summary		
Ownership		
Depreciable value:	$	106,850.00
Equipment depreciation:	$	21,370.00 / Year
Interest expense:	$	10,500.00 / Year
Taxes, license, insurance, and storage:	$	3,150.00 / Year
Annual ownership cost:	$	35,020.00 / Year
Ownership cost (Subtotal)	$	21.89/ Hour
Machine operating		
Repairs and maintenance:	$	8.68 / Hour
Fuel and oil:	$	4.98 / Hour
Lines and rigging:	$	0.50 / Hour
Tires or Tracks	$	1.56 / Hour
Equipment operating cost (Subtotal):	$	15.72 / Hour
Labor:		
Direct labor cost:	$	17.01 / Hour
Supervision and overhead:	$	2.55 / Hour
Labor cost (Subtotal):	$	19.56 / Hour
OWNERSHIP COST	$	21.89 / Hour
OPERATING COST	$	15.72 / Hour
LABOR COST	$	19.56 / Hour
Machine rate (Ownership + Operating + Labor)	$	57.17 / Hour

Table 45. Chainsaw: ownership and operating cost for NEW equipment price.

Equipment Ownership Cost Inputs		
Delivered equipment cost	$	1,000.00
Minus line and rigging cost	$	0.00
Minus tire and track replacement cost	$	0.00
Minus residual (salvage) value	$	200.00
Life of equipment (Years)	#	2.00
Number of days worked per year	#	200.00
Number of hours worked per day	#	8.00
Interest Expense	%	10.00
Percent of average annual investment for:		
Taxes, License, Insurance, and Storage	%	3.00
Equipment Operating Cost Inputs		
Percent of equipment depreciation for repairs	%	75.00
Fuel amount (Gallons per hour)	#	0.25
Fuel cost (Per gallon)	$	1.30
Percent of fuel consumption for lubricants	%	15.00
Cost of oil and lubricants (Per gallon)	$	4.00
Cost of lines	$	30.00
Estimated life of lines (Hours)	#	120.00
Cost of rigging	$	0.00
Estimated life of rigging (Hours)	#	0.00
Cost of tires or tracks	$	0.00
Estimate life of tires or tracks (Hours)	#	0.00
Summary		
Ownership		
Depreciable value:	$	800.00
Equipment depreciation:	$	400.00 / Year
Interest expense:	$	80.0 / Year
Taxes, license, insurance, and storage:	$	24.00 / Year
Annual ownership cost:	$	504.00 / Year
Ownership cost (Subtotal)	$	0.32 / Hour
Machine operating		
Repairs and maintenance:	$	0.19 / Hour
Fuel and oil:	$	0.47 / Hour
Lines and rigging:	$	0.25 / Hour
Tires or Tracks	$	0.00 / Hour
Equipment operating cost (Subtotal):	$	0.91 / Hour
Labor:		
Direct labor cost:	$	0.00 / Hour
Supervision and overhead:	$	0.00 / Hour
Labor cost (Subtotal):	$	0.00 / Hour
OWNERSHIP COST	$	0.32 / Hour
OPERATING COST	$	0.91 / Hour
LABOR COST	$	0.00 / Hour
Machine rate (Ownership + Operating + Labor)	$	1.23 / Hour

Table 46. Stroke-boom delimber: ownership, operating, and labor cost for NEW equipment price.

Equipment Ownership Cost Inputs		
Delivered equipment cost	$	433,000.00
Minus line and rigging cost	$	0.00
Minus tire and track replacement cost	$	0.00
Minus residual (salvage) value	$	108,250.00
Life of equipment (Years)	#	5.00
Number of days worked per year	#	200.00
Number of hours worked per day	#	8.00
Interest Expense	%	10.00
Percent of average annual investment for:		
Taxes, License, Insurance, and Storage	%	3.00
Equipment Operating Cost Inputs		
Percent of equipment depreciation for repairs	%	65.00
Fuel amount (Gallons per hour)	#	4.00
Fuel cost (Per gallon)	$	1.00
Percent of fuel consumption for lubricants	%	7.00
Cost of oil and lubricants (Per gallon)	$	3.5
Cost of lines	$	0.00
Estimated life of lines (Hours)	#	0.00
Cost of rigging	$	0.00
Estimated life of rigging (Hours)	#	0.00
Cost of tires or tracks	$	0.00
Estimate life of tires or tracks (Hours)	#	0.00
Summary		
Ownership		
Depreciable value:	$	324,750.00
Equipment depreciation:	$	64,950.00 / Year
Interest expense:	$	30,310.00 / Year
Taxes, license, insurance, and storage:	$	9,093.00 / Year
Annual ownership cost:	$	104,353.00 / Year
Ownership cost (Subtotal)	$	65.22 / Hour
Machine operating		
Repairs and maintenance:	$	26.39 / Hour
Fuel and oil:	$	4.98 / Hour
Lines and rigging:	$	0.00 / Hour
Tires or Tracks	$	0.00 / Hour
Equipment operating cost (Subtotal):	$	31.37 / Hour
Labor:		
Direct labor cost:	$	18.75 / Hour
Supervision and overhead:	$	2.81 / Hour
Labor cost (Subtotal):	$	21.56 / Hour
OWNERSHIP COST	$	65.22 / Hour
OPERATING COST	$	31.37 / Hour
LABOR COST	$	21.56 / Hour
Machine rate (Ownership + Operating + Labor)	$	118.15 / Hour

Table 47. Ford F-250 pickup: ownership and operating cost for NEW equipment price.

Equipment Ownership Cost Inputs		
Delivered equipment cost	$	20,000.00
Minus line and rigging cost	$	0.00
Minus tire and track replacement cost	$	400.00
Minus residual (salvage) value	$	6,000.00
Life of equipment (Years)	#	4.00
Number of days worked per year	#	200.00
Number of hours worked per day	#	8.00
Interest Expense	%	10.00
Percent of average annual investment for:		
Taxes, License, Insurance, and Storage	%	3.00
Equipment Operating Cost Inputs		
Percent of equipment depreciation for repairs	%	25.00
Fuel amount (Gallons per hour)	#	1.00
Fuel cost (Per gallon)	$	1.00
Percent of fuel consumption for lubricants	%	1.75
Cost of oil and lubricants (Per gallon)	$	4.00
Cost of lines	$	0.00
Estimated life of lines (Hours)	#	0.00
Cost of rigging	$	0.00
Estimated life of rigging (Hours)	#	0.00
Cost of tires or tracks	$	400.00
Estimate life of tires or tracks (Hours)	#	2,000.00
Summary		
Ownership		
Depreciable value:	$	13,600.00
Equipment depreciation:	$	3,400.00 / Year
Interest expense:	$	1475.50 / Year
Taxes, license, insurance, and storage:	$	442.50 / Year
Annual ownership cost:	$	5,317.50 / Year
Ownership cost (Subtotal)	$	3.32 / Hour
Machine operating		
Repairs and maintenance:	$	0.53 / Hour
Fuel and oil:	$	1.07 / Hour
Lines and rigging:	$	0.00 / Hour
Tires or Tracks	$	0.20 / Hour
Equipment operating cost (Subtotal):	$	1.80 / Hour
Labor:		
Direct labor cost:	$	0.00 / Hour
Supervision and overhead:	$	0.00 / Hour
Labor cost (Subtotal):	$	0.00 / Hour
OWNERSHIP COST	$	3.32 / Hour
OPERATING COST	$	1.80 / Hour
LABOR COST	$	0.00 / Hour
Machine rate (Ownership + Operating + Labor)	$	5.12 / Hour

Table 48. Ford F-350 pickup: ownership and operating cost for NEW equipment price.

Equipment Ownership Cost Inputs		
Delivered equipment cost	$	30,000.00
Minus line and rigging cost	$	0.00
Minus tire and track replacement cost	$	400.00
Minus residual (salvage) value	$	9,000.00
Life of equipment (Years)	#	4.00
Number of days worked per year	#	200.00
Number of hours worked per day	#	8.00
Interest Expense	%	10.00
Percent of average annual investment for:		
Taxes, License, Insurance, and Storage	%	3.00
Equipment Operating Cost Inputs		
Percent of equipment depreciation for repairs	%	25.00
Fuel amount (Gallons per hour)	#	1.25
Fuel cost (Per gallon)	$	1.00
Percent of fuel consumption for lubricants	%	1.75
Cost of oil and lubricants (Per gallon)	$	4.00
Cost of lines	$	0.00
Estimated life of lines (Hours)	#	0.00
Cost of rigging	$	0.00
Estimated life of rigging (Hours)	#	0.00
Cost of tires or tracks	$	400.00
Estimate life of tires or tracks (Hours)	#	2,000.00
Summary		
Ownership		
Depreciable value:	$	20,600.00
Equipment depreciation:	$	5,150.00 / Year
Interest expense:	$	2,212.50 / Year
Taxes, license, insurance, and storage:	$	663.75 / Year
Annual ownership cost:	$	8,026.25 / Year
Ownership cost (Subtotal)	$	5.02 / Hour
Machine operating		
Repairs and maintenance:	$	0.80 / Hour
Fuel and oil:	$	1.34 / Hour
Lines and rigging:	$	0.00 / Hour
Tires or Tracks	$	0.20 / Hour
Equipment operating cost (Subtotal):	$	2.34 / Hour
Labor:		
Direct labor cost:	$	0.00 / Hour
Supervision and overhead:	$	00.0 / Hour
Labor cost (Subtotal):	$	0.00 / Hour
OWNERSHIP COST	$	5.02 / Hour
OPERATING COST	$	2.34 / Hour
LABOR COST	$	0.00 / Hour
Machine rate (Ownership + Operating + Labor)	$	7.36 / Hour

Table 49. Fire-fighting trailer: ownership and operating cost for NEW equipment price.

Equipment Ownership Cost Inputs		
Delivered equipment cost	$	3,000.00
Minus line and rigging cost	$	0.00
Minus tire and track replacement cost	$	0.00
Minus residual (salvage) value	$	500.00
Life of equipment (Years)	#	10.00
Number of days worked per year	#	200.00
Number of hours worked per day	#	8.00
Interest Expense	%	10.00
Percent of average annual investment for:		
Taxes, License, Insurance, and Storage	%	3.00
Equipment Operating Cost Inputs		
Percent of equipment depreciation for repairs	%	20.00
Fuel amount (Gallons per hour)	#	0.01
Fuel cost (Per gallon)	$	1.30
Percent of fuel consumption for lubricants	%	1.00
Cost of oil and lubricants (Per gallon)	$	4.00
Cost of lines	$	0.00
Estimated life of lines (Hours)	#	0.00
Cost of rigging	$	0.00
Estimated life of rigging (Hours)	#	0.00
Cost of tires or tracks	$	0.00
Estimate life of tires or tracks (Hours)	#	0.00
Summary		
Ownership		
Depreciable value:	$	2,500.00
Equipment depreciation:	$	250.00 / Year
Interest expense:	$	187.50 / Year
Taxes, license, insurance, and storage:	$	56.25 / Year
Annual ownership cost:	$	493.75 / Year
Ownership cost (Subtotal)	$	0.31 / Hour
Machine operating		
Repairs and maintenance:	$	0.03 / Hour
Fuel and oil:	$	0.01 / Hour
Lines and rigging:	$	0.00 / Hour
Tires or Tracks	$	0.00 / Hour
Equipment operating cost (Subtotal):	$	0.04 / Hour
Labor:		
Direct labor cost:	$	0.00 / Hour
Supervision and overhead:	$	0.00 / Hour
Labor cost (Subtotal):	$	0.00 / Hour
OWNERSHIP COST	$	0.31 / Hour
OPERATING COST	$	0.04 / Hour
LABOR COST	$	0.00 / Hour
Machine rate (Ownership + Operating + Labor)	$	0.35 / Hour

Table 50. Log loader: ownership, operating, and labor cost for NEW equipment price.

Equipment Ownership Cost Inputs		
Delivered equipment cost	$	320,000.00
Minus line and rigging cost	$	0.00
Minus tire and track replacement cost	$	0.00
Minus residual (salvage) value	$	96,000.00
Life of equipment (Years)	#	5.00
Number of days worked per year	#	200.00
Number of hours worked per day	#	10.00
Interest Expense	%	10.00
Percent of average annual investment for:		
Taxes, License, Insurance, and Storage	%	3.00
Equipment Operating Cost Inputs		
Percent of equipment depreciation for repairs	%	65.00
Fuel amount (Gallons per hour)	#	4.00
Fuel cost (Per gallon)	$	1.00
Percent of fuel consumption for lubricants	%	7.00
Cost of oil and lubricants (Per gallon)	$	3.50
Cost of lines	$	0.00
Estimated life of lines (Hours)	#	0.00
Cost of rigging	$	0.00
Estimated life of rigging (Hours)	#	0.00
Cost of tires or tracks	$	0.00
Estimate life of tires or tracks (Hours)	#	0.00
Summary		
Ownership		
Depreciable value:	$	224,000.00
Equipment depreciation:	$	44,850.00 / Year
Interest expense:	$	23,040.00 / Year
Taxes, license, insurance, and storage:	$	6,912.00 / Year
Annual ownership cost:	$	74,752.00 / Year
Ownership cost (Subtotal)	$	37.38 / Hour
Machine operating		
Repairs and maintenance:	$	14.56 / Hour
Fuel and oil:	$	4.98 / Hour
Lines and rigging:	$	0.00 / Hour
Tires or Tracks	$	0.00 / Hour
Equipment operating cost (Subtotal):	$	19.54 / Hour
Labor:		
Direct labor cost:	$	21.00 / Hour
Supervision and overhead:	$	3.15 / Hour
Labor cost (Subtotal):	$	24.15 / Hour
OWNERSHIP COST	$	37.38 / Hour
OPERATING COST	$	19.54 / Hour
LABOR COST	$	24.15 / Hour
Machine rate (Ownership + Operating + Labor)	$	81.07 / Hour

Table 51. Shovel for prebunching: ownership, operating, and labor cost for NEW equipment price.

Equipment Ownership Cost Inputs		
Delivered equipment cost	$	386,000.00
Minus line and rigging cost	$	0.00
Minus tire and track replacement cost	$	10,000.00
Minus residual (salvage) value	$	57,900.00
Life of equipment (Years)	#	5.00
Number of days worked per year	#	200.00
Number of hours worked per day	#	8.00
Interest Expense	%	10.00
Percent of average annual investment for:		
Taxes, License, Insurance, and Storage	%	3.00
Equipment Operating Cost Inputs		
Percent of equipment depreciation for repairs	%	65.00
Fuel amount (Gallons per hour)	#	4.00
Fuel cost (Per gallon)	$	1.00
Percent of fuel consumption for lubricants	%	7.00
Cost of oil and lubricants (Per gallon)	$	3.50
Cost of lines	$	0.00
Estimated life of lines (Hours)	#	0.00
Cost of rigging	$	0.00
Estimated life of rigging (Hours)	#	0.00
Cost of tires or tracks	$	10,000.00
Estimate life of tires or tracks (Hours)	#	6,400.00
Summary		
Ownership		
Depreciable value:	$	318,100.00
Equipment depreciation:	$	63,620.00 / Year
Interest expense:	$	25,476.00 / Year
Taxes, license, insurance, and storage:	$	7,642.00 / Year
Annual ownership cost:	$	96,738.80 / Year
Ownership cost (Subtotal)	$	60.46 / Hour
Machine operating		
Repairs and maintenance:	$	25.85 / Hour
Fuel and oil:	$	4.98 / Hour
Lines and rigging:	$	0.00 / Hour
Tires or Tracks	$	3.13 / Hour
Equipment operating cost (Subtotal):	$	33.95 / Hour
Labor:		
Direct labor cost:	$	23.57 / Hour
Supervision and overhead:	$	3.53 / Hour
Labor cost (Subtotal):	$	27.10 / Hour
OWNERSHIP COST	$	60.46 / Hour
OPERATING COST	$	33.95 / Hour
LABOR COST	$	27.10 / Hour
Machine rate (Ownership + Operating + Labor)	$	121.51 / Hour

Appendix D PACE Output, Used-Equipment Purchase Price

Table 52. Feller-buncher: ownership, operating, and labor cost for USED equipment price.

Equipment Ownership Cost Inputs		
Delivered equipment cost	$	90,000.00
Minus line and rigging cost	$	0.00
Minus tire and track replacement cost	$	10,000.00
Minus residual (salvage) value	$	25,000.00
Life of equipment (Years)	#	4.00
Number of days worked per year	#	200.00
Number of hours worked per day	#	8.00
Interest Expense	%	10.00
Percent of average annual investment for:		
Taxes, License, Insurance, and Storage	%	3.00
Equipment Operating Cost Inputs		
Percent times new equipment repair cost	%	115.00
Fuel amount (Gallons per hour)	#	4.00
Fuel cost (Per gallon)	$	1.00
Percent of fuel consumption for lubricants	%	7.00
Cost of oil and lubricants (Per gallon)	$	3.50
Cost of lines	$	0.00
Estimated life of lines (Hours)	#	0.00
Cost of rigging	$	35,000.00
Estimated life of rigging (Hours)	#	3,200.00
Cost of tires or tracks	$	10,000.00
Estimate life of tires or tracks (Hours)	#	3,200.00
Summary		
Ownership		
Depreciable value:	$	55,000.00
Equipment depreciation:	$	13,750.00 / Year
Interest expense:	$	6,562.50 / Year
Taxes, license, insurance, and storage:	$	1,968.75 / Year
Annual ownership cost:	$	22,281.25 / Year
Ownership cost (Subtotal)	$	13.93 / Hour
Machine operating		
Repairs and maintenance:	$	29.73 / Hour
Fuel and oil:	$	4.98 / Hour
Lines and rigging:	$	10.94/ Hour
Tires or Tracks	$	3.13 / Hour
Equipment operating cost (Subtotal):	$	48.77 / Hour
Labor:		
Direct labor cost:	$	23.57 / Hour
Supervision and overhead:	$	3.53 / Hour
Labor cost (Subtotal):	$	27.10 / Hour
OWNERSHIP COST	$	13.93 / Hour
OPERATING COST	$	48.77 / Hour
LABOR COST	$	27.10 / Hour
Machine rate (Ownership + Operating + Labor)	$	89.80 / Hour

Table 53. Swing-boom skidder: ownership, operating, and labor cost for USED equipment price.

Equipment Ownership Cost Inputs		
Delivered equipment cost	$	40,000.00
Minus line and rigging cost	$	650.00
Minus tire and track replacement cost	$	5,000.00
Minus residual (salvage) value	$	4,000.00
Life of equipment (Years)	#	4.00
Number of days worked per year	#	200.00
Number of hours worked per day	#	8.00
Interest Expense	%	10.00
Percent of average annual investment for:		
Taxes, License, Insurance, and Storage	%	3.00
Equipment Operating Cost Inputs		
Percent times new equipment repair cost	%	115.00
Fuel amount (Gallons per hour)	#	4.00
Fuel cost (Per gallon)	$	1.00
Percent of fuel consumption for lubricants	%	7.00
Cost of oil and lubricants (Per gallon)	$	3.50
Cost of lines	$	150.00
Estimated life of lines (Hours)	#	800.00
Cost of rigging	$	500.00
Estimated life of rigging (Hours)	#	1,600.00
Cost of tires or tracks	$	5,000.00
Estimate life of tires or tracks (Hours)	#	3,200.00
Summary		
Ownership		
Depreciable value:	$	30,350.00
Equipment depreciation:	$	7,587.50 / Year
Interest expense:	$	2,650.00 / Year
Taxes, license, insurance, and storage:	$	795.00 / Year
Annual ownership cost:	$	11,032.50 / Year
Ownership cost (Subtotal)	$	6.90/ Hour
Machine operating		
Repairs and maintenance:	$	9.98 / Hour
Fuel and oil:	$	4.98 / Hour
Lines and rigging:	$	0.50 / Hour
Tires or Tracks	$	1.56 / Hour
Equipment operating cost (Subtotal):	$	17.02 / Hour
Labor:		
Direct labor cost:	$	17.01 / Hour
Supervision and overhead:	$	2.55 / Hour
Labor cost (Subtotal):	$	19.56 / Hour
OWNERSHIP COST	$	6.90 / Hour
OPERATING COST	$	17.02 / Hour
LABOR COST	$	19.56 / Hour
Machine rate (Ownership + Operating + Labor)	$	43.48 / Hour

Table 54. Stroke-boom delimber: ownership, operating, and labor cost for USED equipment price.

Equipment Ownership Cost Inputs		
Delivered equipment cost	$	100,000.00
Minus line and rigging cost	$	0.00
Minus tire and track replacement cost	$	0.00
Minus residual (salvage) value	$	25,000.00
Life of equipment (Years)	#	4.00
Number of days worked per year	#	200.00
Number of hours worked per day	#	8.00
Interest Expense	%	10.00
Percent of average annual investment for:		
Taxes, License, Insurance, and Storage	%	3.00
Equipment Operating Cost Inputs		
Percent times new equipment repair cost	%	115.00
Fuel amount (Gallons per hour)	#	4.00
Fuel cost (Per gallon)	$	1.00
Percent of fuel consumption for lubricants	%	7.00
Cost of oil and lubricants (Per gallon)	$	3.5
Cost of lines	$	0.00
Estimated life of lines (Hours)	#	0.00
Cost of rigging	$	0.00
Estimated life of rigging (Hours)	#	0.00
Cost of tires or tracks	$	0.00
Estimate life of tires or tracks (Hours)	#	0.00
Summary		
Ownership		
Depreciable value:	$	75,000.00
Equipment depreciation:	$	18,750.00 / Year
Interest expense:	$	7,187.00 / Year
Taxes, license, insurance, and storage:	$	2,156.25 / Year
Annual ownership cost:	$	28,093.75 / Year
Ownership cost (Subtotal)	$	17.56 / Hour
Machine operating		
Repairs and maintenance:	$	30.35 / Hour
Fuel and oil:	$	4.98 / Hour
Lines and rigging:	$	0.00 / Hour
Tires or Tracks	$	0.00 / Hour
Equipment operating cost (Subtotal):	$	35.33 / Hour
Labor:		
Direct labor cost:	$	18.75 / Hour
Supervision and overhead:	$	2.81 / Hour
Labor cost (Subtotal):	$	21.56 / Hour
OWNERSHIP COST	$	17.56 / Hour
OPERATING COST	$	35.33 / Hour
LABOR COST	$	21.56 / Hour
Machine rate (Ownership + Operating + Labor)	$	74.45 / Hour

Table 55. Log loader: ownership, operating, and labor cost for USED equipment price.

Equipment Ownership Cost Inputs		
Delivered equipment cost	$	85,000.00
Minus line and rigging cost	$	0.00
Minus tire and track replacement cost	$	0.00
Minus residual (salvage) value	$	20,000.00
Life of equipment (Years)	#	4.00
Number of days worked per year	#	200.00
Number of hours worked per day	#	10.00
Interest Expense	%	10.00
Percent of average annual investment for:		
Taxes, License, Insurance, and Storage	%	3.00
Equipment Operating Cost Inputs		
Percent times new equipment repair cost	%	115.00
Fuel amount (Gallons per hour)	#	4.00
Fuel cost (Per gallon)	$	1.00
Percent of fuel consumption for lubricants	%	7.00
Cost of oil and lubricants (Per gallon)	$	3.50
Cost of lines	$	0.00
Estimated life of lines (Hours)	#	0.00
Cost of rigging	$	0.00
Estimated life of rigging (Hours)	#	0.00
Cost of tires or tracks	$	0.00
Estimate life of tires or tracks (Hours)	#	0.00
Summary		
Ownership		
Depreciable value:	$	65,000.00
Equipment depreciation:	$	16,250.00 / Year
Interest expense:	$	6,062.50 / Year
Taxes, license, insurance, and storage:	$	1,818.75 / Year
Annual ownership cost:	$	24.131.25 / Year
Ownership cost (Subtotal)	$	12.07 / Hour
Machine operating		
Repairs and maintenance:	$	16.74 / Hour
Fuel and oil:	$	4.98 / Hour
Lines and rigging:	$	0.00 / Hour
Tires or Tracks	$	0.00 / Hour
Equipment operating cost (Subtotal):	$	21.72 / Hour
Labor:		
Direct labor cost:	$	21.00 / Hour
Supervision and overhead:	$	3.15 / Hour
Labor cost (Subtotal):	$	24.15 / Hour
OWNERSHIP COST	$	12.07 / Hour
OPERATING COST	$	21.72 / Hour
LABOR COST	$	24.15 / Hour
Machine rate (Ownership + Operating + Labor)	$	57.94 / Hour

Table 56. Shovel for prebunching: ownership, operating, and labor cost for USED equipment price.

Equipment Ownership Cost Inputs		
Delivered equipment cost	$	90,000.00
Minus line and rigging cost	$	0.00
Minus tire and track replacement cost	$	10,000.00
Minus residual (salvage) value	$	25,000.00
Life of equipment (Years)	#	4.00
Number of days worked per year	#	200.00
Number of hours worked per day	#	8.00
Interest Expense	%	10.00
Percent of average annual investment for:		
Taxes, License, Insurance, and Storage	%	3.00
Equipment Operating Cost Inputs		
Percent times new equipment repair cost	%	115.00
Fuel amount (Gallons per hour)	#	4.00
Fuel cost (Per gallon)	$	1.00
Percent of fuel consumption for lubricants	%	7.00
Cost of oil and lubricants (Per gallon)	$	3.50
Cost of lines	$	0.00
Estimated life of lines (Hours)	#	0.00
Cost of rigging	$	0.00
Estimated life of rigging (Hours)	#	0.00
Cost of tires or tracks	$	10,000.00
Estimate life of tires or tracks (Hours)	#	6,400.00
Summary		
Ownership		
Depreciable value:	$	55,000.00
Equipment depreciation:	$	13,750.00 / Year
Interest expense:	$	6,562.50 / Year
Taxes, license, insurance, and storage:	$	1,968.75 / Year
Annual ownership cost:	$	22,281.25 / Year
Ownership cost (Subtotal)	$	13.93 / Hour
Machine operating		
Repairs and maintenance:	$	29.73 / Hour
Fuel and oil:	$	4.98 / Hour
Lines and rigging:	$	0.00 / Hour
Tires or Tracks	$	3.13 / Hour
Equipment operating cost (Subtotal):	$	37.83 / Hour
Labor:		
Direct labor cost:	$	23.57 / Hour
Supervision and overhead:	$	3.53 / Hour
Labor cost (Subtotal):	$	27.10 / Hour
OWNERSHIP COST	$	13.93 / Hour
OPERATING COST	$	37.83 / Hour
LABOR COST	$	27.10 / Hour
Machine rate (Ownership + Operating + Labor)	$	78.86 / Hou

Appendix E Equipment Harvesting Costs Calculations, for Total Harvesting Cost.

Table 57. Total harvesting costs calculations, Scenario I, New equipment cost.

				Harvesting Costs By Blocks (VOLUME CALCULATED BY ALL BLOCKS)										
				INCLUDES ALL PRACTICAL EQUIPMENT ON THE SITE										
	Detail	Shift	Effective	Cycle	Turns per	Logs per	Net Vol.	Net Vol.	Productio	Ow & Op	Cost	weighted ave		TOTAL
2AA	Delay	Delay	Hour	Time	Hour	Turn	per Log	per Turn	(mbf/hour)	Cost	($/mbf)	yarding cost		COST
buncher	0.25	0.22	31.8	0.91	34.94505	2.5	0.13	0.33	11.52	132.45	11.50			($/MBF)
grapple	0.17	0.08	45	4.65	9.677419	11.7	0.13	1.54	14.93	62.65	4.20			
delimber					1	81.7	0.13	10.77	10.77	118.15	10.97			
loader									3.30	81.07	24.57			
swing-boom									4.01	21.89	5.46			
chaser									4.01	20.00	4.99			
laborer									4.01	20.00	4.99			
pick-ups									4.01	12.48	3.11			
saw/fire									4.01	2.81	0.70			
layout									4.01	0.27	0.07			
move in									4.01	2.62	0.65			71.20
	Detail	Shift	Effective	Cycle	Turns per	Logs per	Net Vol.	Net Vol.	MBF per	Ow & Op	Cost			
2AB	Delay	Delay	Hour	Time	Hour	Turn	per Log	per Turn	Hour	Cost	($/MBF)			
buncher	0.07	0.10	49.80	1.02	48.82	2.5	0.13	0.33	16.09	132.45	8.23			
grapple	0.51	0.07	25.20	4.35	5.79	18.3	0.13	2.41	13.98	62.65	4.48			
delimber					1	99.2	0.13	13.08	13.08	118.15	9.03			
loader									3.14	81.07	25.83			
swing-boom									4.12	21.89	5.31			
chaser									4.12	20.00	4.85			
laborer									4.12	20.00	4.85			
pick-ups									4.12	12.48	3.03			
saw/fire									4.12	2.81	0.68			
layout									4.12	2.73	0.66			
move in									4.12	3.34	0.81			67.77
	Detail	Shift	Effective	Cycle	Turns per	Logs per	Net Vol.	Net Vol.	MBF per	Ow & Op	Cost			
2BA	Delay	Delay	Hour	Time	Hour	Turn	per Log	per Turn	Hour	Cost	($/MBF)			
manual	0.41	0.05	32.40	0.89	36.40	2.5	0.13	0.33	12.00	45.00	3.75			
shovel	0.09	0.23	40.80	1.45	28.14	1.5	0.13	0.20	5.57	121.51	21.83			
grapple	0.32	0.19	29.40	4.74	6.20	11	0.13	1.45	9.00	62.65	6.96			
delimber					1	68	0.13	8.97	8.97	118.15	13.18			
loader									3.59	81.07	22.59			
swing-boom									4.98	21.89	4.40			
chaser									4.98	20.00	4.02			
laborer									4.98	20.00	4.02			
pick-ups									4.98	12.48	2.51			
saw/fire									4.98	2.81	0.56			
layout									4.98	0.31	0.06			
move in									4.98	3.06	0.61			84.49
	Detail	Shift	Effective	Cycle	Turns per	Logs per	Net Vol.	Net Vol.	MBF per	Ow & Op	Cost			
2BB	Delay	Delay	Hour	Time	Hour	Turn	per Log	per Turn	Hour	Cost	($/MBF)			
manual	0.30	0.10	36.00	1.64	21.95	2.5	0.13	0.33	7.24	45.00	6.22			
shovel	0.35	0.24	24.60	1.11	22.16	1.5	0.13	0.20	4.38	121.51	27.72			
grapple	0.38	0.19	25.80	4.43	5.82	15	0.13	1.98	11.52	62.65	5.44			
delimber					1	75	0.13	9.89	9.89	118.15	11.95			
loader									3.82	81.07	21.25			
swing-boom									5.44	21.89	4.02			
chaser									5.44	20.00	3.68			
laborer									5.44	20.00	3.68			
pick-ups									5.44	12.48	2.30			
saw/fire									5.44	2.81	0.52			
layout									5.44	3.41	0.63			
move in									5.44	3.34	0.61			88.01
	Detail	Shift	Effective	Cycle	Turns per	Logs per	Net Vol.	Net Vol.	MBF per	Ow & Op	Cost			
5CA	Delay	Delay	Hour	Time	Hour	Turn	per Log	per Turn	Hour	Cost	($/MBF)			
manual	0.37	0.02	36.60	3.95	9.27	2.5	0.13	0.33	3.05	45.00	14.73			
shovel	0.36	0.14	30.00	0.85	35.29	1	0.13	0.13	4.65	121.51	26.11			
grapple	0.50	0.04	27.60	3.92	7.04	10	0.13	1.32	9.28	62.65	6.75	3.71		
swing-boom		0.25	45.00	10.26	4.39	6.44	0.13	0.85	3.72	57.17	15.35	6.91		
loader									4.91	81.07	16.53			
delimber									6.90	118.15	17.12			
chaser									6.90	20.00	2.90			
pick-ups									6.90	12.48	1.81			
saw/fire									6.90	2.81	0.41			
layout									6.90	1.07	0.16			
move in									6.90	6.99	1.01			91.40

Table 58. Total harvesting costs calculations, Scenario II, New equipment cost.

				Harvesting Costs By BLocks (VOLUME CALCULATED BY INDIVIDUAL BLOCKS)										
					INCLUDE ALL PRACTICAL EQUIPMENT ON THE SITE									
	Detail	Shift	Effective	Cycle	Turns per	Logs per	Net Vol.	Net Vol.	Productio	Ow & Op	Cost	weighted ave		TOTAL
2AA	Delay	Delay	Hour	Time	Hour	Turn	per Log	per Turn	(mbf/hour	Cost	($/mbf)	yarding cost		COST
buncher	0.25	0.22	31.8	0.91	34.95	2.5	0.11	0.28	9.70	132.45	13.66			($/MBF)
grapple	0.17	0.08	45	4.65	9.68	11.7	0.11	1.30	12.57	62.65	4.98			
delimber					1	81.7	0.11	9.07	9.07	118.15	13.03			
loader									3.18	81.07	25.49			
swing-boom									3.85	21.89	5.69			
chaser									3.85	20.00	5.19			
laborer									3.85	20.00	5.19			
pick-ups									3.85	12.48	3.24			
sawfire									3.85	2.81	0.73			
layout									3.85	0.27	0.07			
move in									3.85	2.62	0.68			77.96
	Detail	Shift	Effective	Cycle	Turns per	Logs per	Net Vol.	Net Vol.	MBF per	Ow & Op	Cost			
2AB	Delay	Delay	Hour	Time	Hour	Turn	per Log	per Turn	Hour	Cost	($/MBF)			
buncher	0.07	0.10	49.80	1.02	48.82	2.5	0.10	0.26	12.45	132.45	10.64			
grapple	0.51	0.07	25.20	4.35	5.79	18.3	0.10	1.87	10.81	62.65	5.79			
delimber					1	99.2	0.10	10.12	10.12	118.15	11.68			
loader									2.93	81.07	27.68			
swing-boom									3.84	21.89	5.70			
chaser									3.84	20.00	5.20			
laborer									3.84	20.00	5.20			
pick-ups									3.84	12.48	3.25			
sawfire									3.84	2.81	0.73			
layout									3.84	2.73	0.71			
move in									3.84	3.34	0.87			77.46
	Detail	Shift	Effective	Cycle	Turns per	Logs per	Net Vol.	Net Vol.	MBF per	Ow & Op	Cost			
2BA	Delay	Delay	Hour	Time	Hour	Turn	per Log	per Turn	Hour	Cost	($/MBF)			
manual	0.41	0.05	32.40	0.89	36.40	2.5	0.12	0.30	10.78	45.00	4.18			
shovel	0.09	0.23	40.80	1.45	28.14	1.5	0.12	0.18	5.00	121.51	24.32			
grapple	0.32	0.19	29.40	4.74	6.20	11	0.12	1.30	8.08	62.65	7.76			
delimber					1	68	0.12	8.05	8.05	118.15	14.67			
loader									3.45	81.07	23.47			
swing-boom									4.79	21.89	4.57			
chaser									4.79	20.00	4.17			
laborer									4.79	20.00	4.17			
pick-ups									4.79	12.48	2.60			
sawfire									4.79	2.81	0.59			
layout									4.79	0.31	0.06			
move in									4.79	3.06	0.64			91.19
	Detail	Shift	Effective	Cycle	Turns per	Logs per	Net Vol.	Net Vol.	MBF per	Ow & Op	Cost			
2BB	Delay	Delay	Hour	Time	Hour	Turn	per Log	per Turn	Hour	Cost	($/MBF)			
manual	0.30	0.10	36.00	1.64	21.95	2.5	0.12	0.31	6.75	45.00	6.67			
shovel	0.35	0.24	24.60	1.11	22.16	1.5	0.12	0.18	4.09	121.51	29.72			
grapple	0.38	0.19	25.80	4.43	5.82	15	0.12	1.85	10.75	62.65	5.83			
delimber					1	75	0.12	9.23	9.23	118.15	12.81			
loader									3.70	81.07	21.92			
swing-boom									5.27	21.89	4.15			
chaser									5.27	20.00	3.79			
laborer									5.27	20.00	3.79			
pick-ups									5.27	12.48	2.37			
sawfire									5.27	2.81	0.53			
									5.27	3.41	0.63			
									5.27	3.34	0.61			92.83
	Detail	Shift	Effective	Cycle	Turns per	Logs per	Net Vol.	Net Vol.	MBF per	Ow & Op	Cost			
5CA	Delay	Delay	Hour	Time	Hour	Turn	per Log	per Turn	Hour	Cost	($/MBF)			
manual	0.37	0.02	36.60	3.95	9.27	2.5	0.15	0.37	3.41	45.00	13.22			
shovel	0.36	0.14	30.00	0.85	35.29	1	0.15	0.15	5.19	121.51	23.42			
grapple	0.50	0.04	27.60	3.92	7.04	10	0.15	1.47	10.35	62.65	6.05	3.33		
swing-boom		0.25	45.00	10.26	4.39	6.44	0.15	0.95	4.15	57.17	13.77	6.20		
loader									5.16	81.07	15.70			
delimber									7.23	118.15	16.34			
chaser									7.23	20.00	2.77			
pick-ups									7.23	12.48	1.73			
sawfire									7.23	2.81	0.39			
layout									7.23	1.07	0.15			
move in									7.23	6.99	0.97			84.20

Table 59. Total harvesting costs calculations, Scenario I, Used equipment cost.

USED				Harvesting Costs By Blocks (VOLUME CALCULATED BY ALL BLOCKS)										
					INCLUDES ALL PRACTICAL EQUIPMENT ON THE SITE									
	Detail	Shift	Effective	Cycle	Turns per	Logs per	Net Vol.	Net Vol.	Productio	Ow & Op	Cost	weighted ave		TOTAL
2AA	Delay	Delay	Hour	Time	Hour	Turn	per Log	per Turn	(mbf/hour)	Cost	($/mbf)	yarding cost		COST
buncher	0.25	0.22	31.8	0.91	34.94505	2.5	0.13	0.33	11.52	89.80	7.80			($/MBF)
grapple	0.17	0.08	45	4.65	9.677419	11.7	0.13	1.54	14.93	62.65	4.20			
delimber					1	81.7	0.13	10.77	10.77	74.45	6.91			
loader									3.30	57.94	17.56			
swing-boom									4.01	6.90	1.72			
chaser									4.01	20.00	4.99			
laborer									4.01	20.00	4.99			
pick-ups									4.01	12.48	3.11			
saw/fire									4.01	2.81	0.70			
layout									4.01	0.27	0.07			
move in									4.01	2.62	0.65			52.69
	Detail	Shift	Effective	Cycle	Turns per	Logs per	Net Vol.	Net Vol.	MBF per	Ow & Op	Cost			
2AB	Delay	Delay	Hour	Time	Hour	Turn	per Log	per Turn	Hour	Cost	($/MBF)			
buncher	0.07	0.10	49.80	1.02	48.82	2.5	0.13	0.33	16.09	89.80	5.58			
grapple	0.51	0.07	25.20	4.35	5.79	18.3	0.13	2.41	13.98	62.65	4.48			
delimber					1	99.2	0.13	13.08	13.08	74.45	5.69			
loader									3.14	57.94	18.46			
swing-boom									4.12	6.90	1.67			
chaser									4.12	20.00	4.85			
laborer									4.12	20.00	4.85			
pick-ups									4.12	12.48	3.03			
saw/fire									4.12	2.81	0.68			
layout									4.12	2.73	0.66			
move in									4.12	3.34	0.81			50.78
	Detail	Shift	Effective	Cycle	Turns per	Logs per	Net Vol.	Net Vol.	MBF per	Ow & Op	Cost			
2BA	Delay	Delay	Hour	Time	Hour	Turn	per Log	per Turn	Hour	Cost	($/MBF)			
manual	0.41	0.05	32.40	0.89	36.40	2.5	0.13	0.33	12.00	45.00	3.75			
shovel	0.09	0.23	40.80	1.45	28.14	1.5	0.13	0.20	5.57	78.86	14.17			
grapple	0.32	0.19	29.40	4.74	6.20	11	0.13	1.45	9.00	62.65	6.96			
delimber					1	68	0.13	8.97	8.97	74.45	8.30			
loader									3.59	57.94	16.15			
swing-boom									4.98	6.90	1.39			
chaser									4.98	20.00	4.02			
laborer									4.98	20.00	4.02			
pick-ups									4.98	12.48	2.51			
saw/fire									4.98	2.81	0.56			
layout									4.98	0.31	0.06			
move in									4.98	3.06	0.61			62.50
	Detail	Shift	Effective	Cycle	Turns per	Logs per	Net Vol.	Net Vol.	MBF per	Ow & Op	Cost			
2BB	Delay	Delay	Hour	Time	Hour	Turn	per Log	per Turn	Hour	Cost	($/MBF)			
manual	0.30	0.10	36.00	1.64	21.95	2.5	0.13	0.33	7.24	45.00	6.22			
shovel	0.35	0.24	24.60	1.11	22.16	1.5	0.13	0.20	4.38	78.86	17.99			
grapple	0.38	0.19	25.80	4.43	5.82	15	0.13	1.98	11.52	62.65	5.44			
delimber					1	75	0.13	9.89	9.89	74.45	7.53			
loader									3.82	57.94	15.19			
swing-boom									5.44	6.90	1.27			
chaser									5.44	20.00	3.68			
laborer									5.44	20.00	3.68			
pick-ups									5.44	12.48	2.30			
saw/fire									5.44	2.81	0.52			
layout									5.44	3.41	0.63			
move in									5.44	3.34	0.61			65.04
	Detail	Shift	Effective	Cycle	Turns per	Logs per	Net Vol.	Net Vol.	MBF per	Ow & Op	Cost			
5CA	Delay	Delay	Hour	Time	Hour	Turn	per Log	per Turn	Hour	Cost	($/MBF)			
manual	0.37	0.02	36.60	3.95	9.27	2.5	0.13	0.33	3.05	45.00	14.73			
shovel	0.36	0.14	30.00	0.85	35.29	1	0.13	0.13	4.65	78.86	16.94			
grapple	0.50	0.04	27.60	3.92	7.04	10	0.13	1.32	9.28	62.65	6.75	3.71		
swing-boom		0.25	45.00	10.26	4.39	6.44	0.13	0.85	3.72	43.48	11.67	5.25		
loader									4.91	57.94	11.81			
delimber									6.90	74.45	10.79			
chaser									6.90	20.00	2.90			
pick-ups									6.90	12.48	1.81			
saw/fire									6.90	2.81	0.41			
layout									6.90	1.07	0.16			
move in									6.90	6.99	1.01			69.53

Table 60. Total harvesting costs calculations, Scenario II, Used equipment cost.

USED				Harvesting Costs By BLocks (VOLUME CALCULATED BY INDIVIDUAL BLOCKS)										
					INCLUDE ALL PRACTICAL EQUIPMENT ON THE SITE									
	Detail	Shift	Effective	Cycle	Turns per	Logs per	Net Vol.	Net Vol.	Productio	Ow & Op	Cost	weighted ave		TOTAL
2AA	Delay	Delay	Hour	Time	Hour	Turn	per Log	per Turn	(mbf/hour	Cost	($/mbf)	yarding cost		COST
buncher	0.25	0.22	31.8	0.91	34.95	2.5	0.11	0.28	9.70	89.80	9.26			($/MBF)
grapple	0.17	0.08	45	4.65	9.68	11.7	0.11	1.30	12.57	62.65	4.98			
delimber					1	81.7	0.11	9.07	9.07	74.45	8.21			
loader									3.18	57.94	18.22			
swing-boom									3.85	6.90	1.79			
chaser									3.85	20.00	5.19			
laborer									3.85	20.00	5.19			
pick-ups									3.85	12.48	3.24			
saw/fire									3.85	2.81	0.73			
layout									3.85	0.27	0.07			
move in									3.85	2.62	0.68			57.58
	Detail	Shift	Effective	Cycle	Turns per	Logs per	Net Vol.	Net Vol.	MBF per	Ow & Op	Cost			
2AB	Delay	Delay	Hour	Time	Hour	Turn	per Log	per Turn	Hour	Cost	($/MBF)			
buncher	0.07	0.10	49.80	1.02	48.82	2.5	0.10	0.26	12.45	89.80	7.21			
grapple	0.51	0.07	25.20	4.35	5.79	18.3	0.10	1.87	10.81	62.65	5.79			
delimber					1	99.2	0.10	10.12	10.12	74.45	7.36			
loader									2.93	57.94	19.78			
swing-boom									3.84	6.90	1.80			
chaser									3.84	20.00	5.20			
laborer									3.84	20.00	5.20			
pick-ups									3.84	12.48	3.25			
saw/fire									3.84	2.81	0.73			
layout									3.84	2.73	0.71			
move in									3.84	3.34	0.87			57.91
	Detail	Shift	Effective	Cycle	Turns per	Logs per	Net Vol.	Net Vol.	MBF per	Ow & Op	Cost			
2BA	Delay	Delay	Hour	Time	Hour	Turn	per Log	per Turn	Hour	Cost	($/MBF)			
manual	0.41	0.05	32.40	0.89	36.40	2.5	0.12	0.30	10.78	45.00	4.18			
shovel	0.09	0.23	40.80	1.45	28.14	1.5	0.12	0.18	5.00	78.86	15.78			
grapple	0.32	0.19	29.40	4.74	6.20	11	0.12	1.30	8.08	62.65	7.76			
delimber					1	68	0.12	8.05	8.05	74.45	9.25			
loader									3.45	57.94	16.77			
swing-boom									4.79	6.90	1.44			
chaser									4.79	20.00	4.17			
laborer									4.79	20.00	4.17			
pick-ups									4.79	12.48	2.60			
saw/fire									4.79	2.81	0.59			
layout									4.79	0.31	0.06			
move in									4.79	3.06	0.64			67.41
	Detail	Shift	Effective	Cycle	Turns per	Logs per	Net Vol.	Net Vol.	MBF per	Ow & Op	Cost			
2BB	Delay	Delay	Hour	Time	Hour	Turn	per Log	per Turn	Hour	Cost	($/MBF)			
manual	0.30	0.10	36.00	1.64	21.95	2.5	0.12	0.31	6.75	45.00	6.67			
shovel	0.35	0.24	24.60	1.11	22.16	1.5	0.12	0.18	4.09	78.86	19.29			
grapple	0.38	0.19	25.80	4.43	5.82	15	0.12	1.85	10.75	62.65	5.83			
delimber					1	75	0.12	9.23	9.23	74.45	8.07			
loader									3.70	57.94	15.67			
swing-boom									5.27	6.90	1.31			
chaser									5.27	20.00	3.79			
laborer									5.27	20.00	3.79			
pick-ups									5.27	12.48	2.37			
saw/fire									5.27	2.81	0.53			
									5.27	3.41	0.63			
									5.27	3.34	0.61			68.56
	Detail	Shift	Effective	Cycle	Turns per	Logs per	Net Vol.	Net Vol.	MBF per	Ow & Op	Cost			
5CA	Delay	Delay	Hour	Time	Hour	Turn	per Log	per Turn	Hour	Cost	($/MBF)			
manual	0.37	0.02	36.60	3.95	9.27	2.5	0.15	0.37	3.41	45.00	13.22			
shovel	0.36	0.14	30.00	0.85	35.29	1	0.15	0.15	5.19	78.86	15.20			
grapple	0.50	0.04	27.60	3.92	7.04	10	0.15	1.47	10.35	62.65	6.05	3.33		
swing-boom		0.25	45.00	10.26	4.39	6.44	0.15	0.95	4.15	43.48	10.47	4.71		
loader									5.16	57.94	11.22			
delimber									7.23	74.45	10.30			
chaser									7.23	20.00	2.77			
pick-ups									7.23	12.48	1.73			
saw/fire									7.23	2.81	0.39			
layout									7.23	1.07	0.15			
move in									7.23	6.99	0.97			63.97

Appendix F Shift Level Forms

Figure 30. Weekly layout summary.

OSU Forest Engineering Study

WSIR Noble Fir

Weekly Layout Summary

Day	Data (mm/dd/yy)	Unit #[1]	Personal hours spent by crew on each activity (1/4 hour increments): General Recon	Tree Marking	Locating Roads	Sale Admin.	Office Analysis	Total Hours
Sun								
Mon								
Tue								
Wed								
Thur								
Fri								
Sat								

[1] Unit # - (Unit#, harvest system, layout) i.e. 1BA, 2DB, etc. or ALL for all areas

COMMENTS (provide any additional information that helps to explain the week's production)

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Figure 31. Feller-buncher, daily shift level form.

OSU Forest Engineering

WSIR Noble Fir Study

Daily Feller-Buncher Production

GENERAL INFORMATION

Date________

Operator________________

Unit[1] 2AA 2AB
(unit#, harvest system, layout)

Start Time_________

End Time_________

Weather: sunny cloudy rain **Temperature**: hot mild cool

Break Time_________

FELLER-BUNCHER PRODUCTION

Total # trees______

DELAYS (greater than 10 minutes)

Minutes	Type[2]	Description of Delay
	Maintenance Mechanical Personal Other	
	Maintenance Mechanical Personal Other	
	Maintenance Mechanical Personal Other	
	Maintenance Mechanical Personal Other	
	Maintenance Mechanical Personal Other	

COMMENTS (provide any additional information that helps to explain the day's production)

[1]Unit
Start a new form when moving to a different unit

QUESTIONS: Peter Matzka (541) 737-3476
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[2]Delay Types
Maintenance - Any time spent on regular maintenance of the skidder during the shift
Mechanical - Any delay related to the mechanical failure of the skidder
Personal - Operator related delay time (water, communication, etc.)

Other - Specify nature of delay (i.e. skid trail blocked, bees nest)

Figure 32. Loader, daily shift level form.

OSU Forest Engineering

WSIR Noble Fir Study

Daily Loader Production

GENERAL INFORMATION

Date_________

Operator________________

Unit[1] 2AA 2AB 2BA 2BB 5CA 5CB 5DA 5DB
(unit#, harvest system, layout)

Start Time_________

End Time_________

Weather: sunny cloudy rain **Temperature**: hot mild cool

Break Time_________

LOAD TICKET INFORMATION

Ticket #________	Ticket #________	Ticket #________
Ticket #________	Ticket #________	Ticket #________
Ticket #________	Ticket #________	Ticket #________
Ticket #________	Ticket #________	Ticket #________

DELAYS (greater than 10 minutes)

Minutes	Type[2]	Description of Delay
	Maintenance Mechanical Personal Other	
	Maintenance Mechanical Personal Other	
	Maintenance Mechanical Personal Other	
	Maintenance Mechanical Personal Other	

COMMENTS (provide any additional information that helps to explain the day's production)

[1]Unit
Start a new form when moving to a different unit

QUESTIONS: Peter Matzka (541) 737-3476
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[2]Delay Types
Maintenance - Any time spent on regular maintenance of the skidder during the shift
Mechanical - Any delay related to the mechanical failure of the skidder
Personal - Operator related delay time (water, communication, etc.)

Other - Specify nature of delay (i.e. skid trail blocked, bees nest)

Figure 33. Stroke-boom delimber, daily shift level form.

OSU Forest Engineering — WSIR Noble Fir Study

Daily Delimber Production

GENERAL INFORMATION

Date_________	**Operator**________________
Unit[1] 2AA 2AB 2BA 2BB 5CA 5CB (unit#, harvest system, layout)	**Start Time**_________
	End Time_________
Weather: sunny cloudy rain **Temperature**: hot mild cool	**Break Time**_________

DELIMBER PRODUCTION

Total # whole tree, partial trees, or log lengths_________

DELAYS (greater than 10 minutes)

Minutes	Type[2]	Description of Delay
	Maintenance Mechanical Personal Other	
	Maintenance Mechanical Personal Other	
	Maintenance Mechanical Personal Other	
	Maintenance Mechanical Personal Other	
	Maintenance Mechanical Personal Other	

COMMENTS (provide any additional information that helps to explain the day's production)

[1]Unit
Start a new form when moving to a different unit

QUESTIONS: Peter Matzka (541) 737-3476
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[2]Delay Types
Maintenance - Any time spent on regular maintenance of the skidder during the shift
Mechanical - Any delay related to the mechanical failure of the skidder
Personal - Operator related delay time (water, communication, etc.)

Other - Specify nature of delay (i.e. skid trail blocked, bees nest)

Figure 34. Grapple skidder and rubber-tired skidder equipped with a winch line, daily shift level form.

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Daily Skidding Production

GENERAL INFORMATION

Date_________ **Operator**________________

Unit[1] 2AA 2AB 2BA 2BB 5CA 5CB 5DA 5DB **Start Time**_________
(unit#, harvest system, layout)

End Time_________

Average Skidding Distance__________(ft)

Break Time_________

Weather: sunny cloudy rain **Temperature:** hot mild cool

SKIDDER PRODUCTION

Total # turns______ Total # logs______ Total # tops______

DELAYS (greater than 10 minutes)

Minutes	Type[2]	Description of Delay
	Maintenance Mechanical Personal Other	
	Maintenance Mechanical Personal Other	
	Maintenance Mechanical Personal Other	
	Maintenance Mechanical Personal Other	
	Maintenance Mechanical Personal Other	

COMMENTS (provide any additional information that helps to explain the day's production)

[1]Unit
Start a new form when moving to a different unit

QUESTIONS: Peter Matzka (541) 737-3476
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[2]Delay Types
Maintenance - Any time spent on regular maintenance of the skidder during the shift
Mechanical - Any delay related to the mechanical failure of the skidder
Personal - Operator related delay time (water, communication, etc.)

Other - Specify nature of delay (i.e. skid trail blocked, bees nest)

Figure 35. Manual felling, daily shift level form.

OSU Forest Engineering WSIR Noble Fir Study

Daily Felling Production

GENERAL INFORMATION

Date__________	**Start Time**__________
Unit[1] 2BA 2BB 5CA 5CB 5DA 5DB (unit#, harvest system, layout)	**End Time**__________
	Break Time__________
Weather: sunny cloudy rain **Temperature**: hot mild cool	

FELLING PRODUCTION

	NAME	HOURS WORKED	TREES CUT
Feller #1			
Feller #2			
Feller #3			
Feller #4			
Feller #5			
Feller #6			

MECHANICAL DELAYS (greater than 10 minutes)

Minutes	Feller #	Description of Delay

OTHER DELAYS (greater than 10 minutes)

Minutes	Feller #	Description of Delay

COMMENTS (provide any additional information that helps to explain the day's production)

[1]Unit
Start a new form when moving to a different unit

QUESTIONS: Peter Matzka (541) 737-3476
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Figure 36. Shovel for prebunching, daily shift level form.

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Daily Shovel (Prebunching) Production

GENERAL INFORMATION

Date________ | **Operator**________________

Unit[1] 2BA 2BB 5CA 5CB
(unit#, harvest system, layout) | **Start Time**__________

End Time__________

Weather: sunny cloudy rain **Temperature**: hot mild cool | **Break Time**__________

SHOVEL (PREBUNCHING) PRODUCTION

Total # trees______

DELAYS (greater than 10 minutes)

Minutes	Type[2]	Description of Delay
	Maintenance Mechanical Personal Other	
	Maintenance Mechanical Personal Other	
	Maintenance Mechanical Personal Other	
	Maintenance Mechanical Personal Other	
	Maintenance Mechanical Personal Other	

COMMENTS (provide any additional information that helps to explain the day's production)

[1]Unit
Start a new form when moving to a different unit

[2]Delay Types
Maintenance - Any time spent on regular maintenance of the skidder during the shift
Mechanical - Any delay related to the mechanical failure of the skidder
Personal - Operator related delay time (water, communication, etc.)

Other - Specify nature of delay (i.e. skid trail blocked, bees nest)

QUESTIONS:
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Appendix G Cost Tree Diagram

Figure 37. Cost Tree Diagram.