AN ABSTRACT OF THE THESIS OF

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Abstract approved: _[signature]_
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Fire exclusion in the western U.S.A. has caused fuel loads to build up and overall forest health to decline. Managers are now looking for ways to reduce these fuel loads while reintroducing some of the desired effects of natural wildfire. One method to do this is thinning using mechanical harvesting methods to reduce fuel loads. This study looks at mechanical thinning in ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*) stands in the Blue Mountains of Northeastern Oregon.

A 409 acre (165.5 ha) unit of 7.1 inch (18 cm) average diameter at breast height was studied during the summer of 1998. Three feller-bunchers and three forwarders were observed in this cut-to-length (shortwood) operation. The three feller-bunchers were a Rottne SMV Rapid EGS, John Deere 653E, and a Caterpillar 320L Excavator, and three forwarders were a Timbco TF815-C, Rottne SMV Rapid, and a Rottne Rapid. These six machines operated on 409 acres (165.5 ha) removing a total of 15,786 tons (14,320 metric tons), 73.4% as sawlogs with the remaining 26.6% as pulp.

Felling and processing costs for the three feller-bunchers were $5.20/ton (5.35 euros[1]/mton) for the Rottne, $6.63/ton (6.83 euros/mton) for the John Deere, and $7.97/ton (8.21 euros/mton) for the Caterpillar Excavator. Forwarding costs were

[1] Euro to dollar exchange rate taken from the April 6, 1999 *Oregonian*.

$7.12/ton (7.33 euros/mton) for the Timbco, $7.61 (7.83 euros/mton) for the Rottne SMV Rapid, and $7.58/ton (7.80 euros/mton) for the Rottne Rapid. Total stump-to-landing costs ranged from $12.27/ton to $15.81/ton (12.63 to 16.28 euros/ton).

Hungry Bob Harvest Production Study: Mechanical Thinning for Fuel Reduction in the Blue Mountains of Northeast Oregon

by

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APPROVED:

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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.

Elizabeth Dodson Coulter, Author

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Hungry Bob Harvest Production Study: Mechanical Thinning for Fuel Reduction in the Blue Mountains of Northeast Oregon

1.0 Introduction

The Hungry Bob Harvesting Production Study is a portion of a larger study, the Hungry Bob Fuels Reduction Study, looking at replicating the historical effects of natural wildfires once had on the forested ecosystems of northeastern Oregon. The harvesting production study looked at the economics and production of mechanical thinning for fuel reduction in the Blue Mountains of Northeastern Oregon. Three feller-bunchers: the Rottne SMV Rapid EGS, John Deere 653E, and Caterpillar 320L, and three forwarders: the Timbco TF815-C, Rottne SMV Rapid, and Rottne Rapid, were used to complete the harvesting of 409 acres. The objectives of the harvest production study were to determine production and costs differences between the various machines.

2.0 Literature Review

2.1 Similar Studies

A history of fire suppression and exclusion has left many of our western forests dense and unhealthy (Agee, 1990). This has lead to a series of studies in the Blue Mountains of northeastern Oregon. The first study in this series was performed during the summer of 1994. This pilot project, named the Deerhorn project, looked at combining a single-grip harvester with a skyline system on relatively flat terrain (Brown, 1995). The 40-acre mixed-conifer stand had an average diameter at breast height of 9 inches and in some areas of the stand had over 1,000 stems per acre (Brown and Kellogg, 1996). The goals of the Deerhorn projects were to decrease fuel loads, increase stand vigor, and promote old-growth characteristics while minimizing soil damage and harvesting costs. Production of the single-grip harvester was approximately double that of the skyline system at 13.5 tons/SMH (scheduled machine hour, or production including delays) for the single-grip harvester as compared to 7.0 tons/SMH for the skyline system (Kellogg and Brown, 1995). This production lead to a unit cost of $6.97/ton for the harvester and $17.74/ton for the yarding for a total stump-to-landing cost of $25.71/ton. Of the material removed, 42% was standing live stems, 14% standing dead, and 44% down dead (Kellogg and Brown, 1995). The inconsistent production rates suggested to managers and researchers that it may be more beneficial as well as more cost efficient if the single-grip harvester also bunched the wood for the skyline system (McIver, 1995). This served as the basis for the next project.

The next project in this series was undertaken between 1995 and 1997. The Limber Jim Fuel Reduction Project utilized two harvesting systems. The first was similar to the harvesting methods used in the Deerhorn project except that the wood was bunched by a feller-buncher before yarding. The second harvesting system used consisted on a feller-buncher and a forwarder. In this study, 88% of the material removed by the skyline system and 94% of the material removed by the forwarder system was pulp and was chipped at the landing. This chipping cost is not reflected in the stump-to-landing cost per ton in order to more easily compare the studies. The stump-to-landing costs for the two systems were $50.01/ton for the skyline system and $18.79/ton for the forwarder system. Soil disturbance was also measured and was statistically identical between the two systems (Drews et al., 1998). This combination of identical soil damage and unequal production costs lead to the use of feller-bunchers and forwarders on the Hungry Bob Fuels Reduction Study, of which the Hungry Bob Harvesting Production Study is a portion.

2.2 GPS in Harvesting Production Studies

Global Positioning Systems (GPS) came into being in 1958 and were used for surveying applications beginning in 1967 (Wolf and Brinker, 1994). GPS have been used extensively by the military (Grant, 1997), wildlife researchers ((Kung and Alvarez-Cordero, 1997), meteorologists (Taylor, 1996), geologists (O'dell, Householder, and Reid,1996), archaeologists (Wakeman and Laumbach, 1997), rental cars (Chisholm and Brown, 1996), NASA engineers (Boyd et al., 1997), and farmers (Rawlins, 1995). The use of GPS to track forest machine productivity is also becoming more prominent. One recent study where GPS was utilized was the Blue Ridge Harvesting Options Study in Little Rock, Washington during the spring and summer of 1998. Here, GPS units were placed on a Caterpillar D5H TSK, Koehring 6644 Shovel, and Timbco 445B feller-buncher and the production of each tracked (Reutebuch, 1999). The only problem encountered on this study was due to the movement of the boom on the feller-buncher, which is discussed later in section 5.1.3. Overall, GPS is a mature technology and is making its way into the toolbag of the harvesting production researcher.

3.0 Study Design

3.1 Study Objectives

The harvesting production study associated with the Hungry Bob Fuels Reduction Study was designed to measure the costs and production associated with a mechanical thinning operation involving feller-bunchers and forwarders in predominantly ponderosa pine (*Pinus ponderosa*) as well as Douglas-fir (*Pseudotsuga menziesii*) stands in the Blue Mountains of northeastern Oregon. More specifically, the study began with the following hypothesis:

1. The production per hour (tons/SMH, or scheduled machine hour) and cost per ton ($/ton) of three feller-bunchers is the same.

    H_0: There is no difference between production per hour and cost per ton of the three feller-bunchers.

    H_1: There is a difference between at least two of the feller-buncher's production per hour and cost per ton.

2. The production per hour (tons/SMH) and cost per ton ($/ton) of three forwarders is the same.

    H_0: There is no difference between production per hour and cost per ton of the three forwarders.

    H_1: There is a difference between at least two of the forwarder's production per hour and cost per ton.

3. No difference in GPS, detailed, and shift-level production (tons/SMH) and cost per ton ($/ton) exists.

   H_0: There is no difference between GPS, detailed, and shift-level production per hour and cost per ton.

   H_1: There is a difference between GPS and detailed, GPS and shift-level, or detailed and shift-level production per hour and cost per ton.

4. Feller-buncher production per hour (tons/SMH) and cost per ton ($/ton) can be explained by the distance traveled, the diameter of the tree cut, the species of the tree cut, and tree position (standing green vs. standing dead vs. down dead).

   H_0: Feller-buncher production per hour and cost per ton can be explained by distance, diameter, species, and tree position.

   H_1: Feller-buncher production per hour and cost per ton can not be explained by one or more of distance, diameter, species, or tree position.

5. Forwarder production per hour (tons/SMH) and cost per ton ($/ton) can be explained by the number of pieces per load, the number of loading stops made, percent sawlog composition, distance traveled, and species composition.

   H_0: Forwarder production per hour and cost per ton can be explained by the number of pieces, stops, percent sawlogs, distance, and species composition.

   H_1: Forwarder production per hour and cost per ton can not be explained by one or more of pieces, stops, percent sawlogs, distance, and species composition.

3.2 Methods of Testing Hypotheses

The hypotheses stated in 3.1 were tested using regression analysis in Microsoft Excel 97 and t-tests in SPSS for Windows 9.0.0 (Statistical Package for the Social Sciences).

3.3 Study Design

3.3.1 Study Site Selection

The Hungry Bob harvesting production study is a portion of a larger study, the Hungry Bob Fuels Reduction Study. This larger study is looking at alternative methods for reintroducing the natural effects of wildfire into managed forests as well as reducing fuel loads. The three alternative methods being studied are mechanical thinning, mechanical thinning followed by a prescribed underburn, and a prescribed underburn alone. These three treatments along with control units were distributed across the study area using a randomized block design. This designated the units that would be studied during the harvest production portion of the study. The units studied during the harvest production study consisted of all the thin and thin/burn units. The study units were also a portion of the Hungry Bob timber sale. The timber sale included units outside the confines of the research. This is the reason unit number designations for the harvest units studied are not continuous.

For the harvest production study all units were assumed to be the same. This assumption was tested through the regression analysis presented later. Unit was not significant in any of the regressions, therefore individual stands did not significantly affect production. Therefore, unit numbers are used as geographical identifiers only.

The nine harvest units studied, the range of dates units were harvested, and the types of data recorded in each are shown in Table 3.1. Because the individual unit did not affect production, there was no need to randomize the order in which units were harvested. If randomization had been done many days would have been lost to moving equipment from one unit to another. Therefore, the order units were harvested in was determined by geography. Machines started in the western portion of the timber sale and moved east.

Table 3.1 Study unit dates, duration, and data

Unit	Date Started	Date Completed	Feller-Buncher Days	Forwarder Days	Detailed Time Study	Shift-level Time Study	GPS Tracking
6	July 15	July 29	18	16	X	X	X[1]
7	July 28	August 6	13	13	X	X	
8	September 21	October 16	16	14		X	
9	August 5	August 17	19	19	X	X	
10	October 2	October 26	14	15		X	
11	August 18	August 21	4	2	X	X	
12	August 12	August 19	6	4	X	X	
22	July 8	July 15	12	10	X	X	X
25	October 23	October 26	2	1		X	

[1]Approximately ½ of the unit was covered with the GPS

3.3.2 Data Collection Methodology Selection

Three data collection methods were selected for the Hungry Bob Harvest Production Study. These three collection methods were detailed time studies, shift-level time studies, and GPS tracking of the forwarder.

3.3.2.1 Detailed Time Studies

Detailed time studies involve a researcher watching a forest operation and recording the time required to perform each task, as well as descriptive data such as distance traveled. Detailed time studies are designed to record all productive tasks as well as small delays, defined as those spanning less than 10 minutes. This data can then be used to create models that describe the effect of the many influencing parameters, such as diameter and travel distance, on production. Delay estimates, or the percentage of time when a machine is actually productive, can also be determined from detailed time study data.

Detailed time studies were chosen because of the flexibility of the models produced. These models can be applied to a range of conditions and therefore are more helpful to managers and others using these models.

3.3.2.2 Shift-level Time Studies

Shift-level time studies involve an operator filling out a shift report at the end of each workday detailing the total production for the day, total hours worked, delays longer than 10 minutes as well as the reason for the delays. This data can then produce models that predict average production for each forest machine. The percentage of time occupied by large delays is also recorded, an important factor in determining $/SMH machine rates as well as adjusting estimates of production based on productive time to a more reasonable level of expected production.

Models from shift-level time studies can be used only within the conditions experienced when the data was being taken. This data however does give a good estimate of long-term production and delays.

3.3.2.3 GPS Tracking

GPS technology was used to spatially trck where a forest machine traveled and the time it spent at each location. Researchers have the ability to extract travel paths, travel distances, number of passes on a trail, turn times, and area impacted by skid trails from GPS data. This level of information is intermediate between detailed and shift-level time studies.

GPS was used for the Hungry Bob harvesting production study because of its ability to give researchers a detailed account of where forwarders traveled, the time it took to complete each turn, the distance traveled, as well as large delays. The data covered every turn in a workday with minimal effort on the part of the researcher and the operator to collect. The goal was to use data collected with the GPS to validate detailed production models. GPS data collected can also be used by other researchers on the Hungry Bob Fuels Reduction Study to look at soil impacts to the residual stand.

<u>3.3.3 Sampling</u>

3.3.3.1 Sample Selection

Shift-level and GPS data represented a 100% sample. On all days all operators filled out shift reports. When the GPS units were functional, both forwarders working in the research units were recording data throughout the day, every day.

Detailed time study data was the only data set that was composed of a sample. Each day of harvesting researchers attempted to get at least half an hour, generally more, worth of data on each harvester and at least one forwarder cycle. This insured that the sample within each unit would be distributed relatively equally between each of the machines working in that unit.

3.3.3.2 Sample Size

Appropriate sample sizes were calculated before field data was collected in order to insure statistically acceptable samples. Sample sizes were calculated using the following equation (Avery and Burkhart, 1994):

$$n = (ts/E)^2$$

Where:

n = desired sample size

t = t value (2-tailed), generally assumed to be 2 for 95% confidence levels

s = estimated standard deviation

E = desired half-width of the confidence interval

3.3.3.2.1 Feller-Buncher Sample Size

For the feller-buncher, the standard deviation used for this calculation was estimated from previous studies and assumed to be 0.28 minutes. The half-width of the confidence interval was 5% of the total average cycle time of 0.8 minutes. This was also estimated from previous studies as well as some preliminary field data. This gave the following calculation:

$$n = [(2*0.28) / (.05 * 0.8)]^2$$

$$n = 196$$

In order to be certain the particular unit did not affect production of the individual machines, at least this sample size was the target number of turns for each machine in each unit.

3.3.3.2.2 Forwarder Sample Size

For the forwarder, the standard deviation was also estimated from previous studies at 7.2 minutes. The half-width of the confidence interval was 10% of the total average cycle time of 45 minutes. This cycle time was estimated from previous studies as well as preliminary field data. A relatively large confidence level of 10% was chosen because of the large variability of cycle times found in other studies and preliminary data. These estimates gave the following target sample size:

$$n = [(2*7.2) / (0.1 * 45)]^2$$

$$n = 11$$

Because of the large variability found in forwarder production, the individual units were not assumed to have any effect on the production of individual forwarders. For this reason, the sample size was assumed to reflect the total number of samples required to reach the desired accuracy.

3.3.4 Equipment Selection

Equipment selection involved deciding the forest machinery, both feller-bunchers, forwarders, and GPS units, to be used.

3.3.4.1 Feller-bunchers

There are many variations of feller-bunchers and harvesters working in the woods today. Harvesters are similar to feller-buncher except that they do not process any of the trees they cut into log lengths. This approach does not work well when the use of short-wood forwarders. Therefore, the use of harvesters as opposed to feller-bunchers was ruled out.

The large range of feller-bunchers found in the woods lead us to choose three machines, a Caterpillar 320L Excavator with a Keto 500 processing head, a John Deere 653E with a Waratah Warrior processing head, and a Rottne SMV Rapid EGS.

Loggers have often modified machines to work in the woods, and the Caterpillar 320L Excavator is no exception. The Cat Exc. is the same machine that is often used to build road or modified to load trucks. Many loaders and excavators have been converted to feller-bunchers by replacing the bucket or grapple with a processing head, as this one had.

A number of purpose-built machines are also working in the woods. For this study we chose the John Deere 654E. The John Deere is designed to be a feller-buncher, as can be seen in the zero tail swing design. This machine represents the middle of the spectrum of what can be found working today as far as cost and sophistication.

At the upper end of the spectrum of what can be found working in the forests today are some of the sophisticated European feller-bunchers. These machines are fast and designed to be profitable in smaller timber. The Rottne SMV Rapid EGS was chosen to represent these types of machines.

3.3.4.2 Forwarders

The wide variation found in the feller-bunchers is not the case with forwarders found working in the woods today. Forwarders are not the type of machine that can be created by modifying another. Therefore the selection of forwarders was not as critical as the selection of feller-bunchers. For this reason, the Timbco TF815-C, Rottne SMV Rapid, and the Rottne Rapid were chosen for this study. All three machines are representative of the types of machines found working across the Northwest.

3.3.4.3 GPS Units

For this study, a rugged, durable GPS unit was required, as the units would be riding around on forwarders working in the field. A number of GPS units were looked at for use in this study, such as those produced by Corvallis MicroTechnology. The Trimble Pro XR was chosen for a combination of reasons. First, the Trimble Pro XR is a mappint grade, sub-meter unit as opposed to a survey grade or recreational unit. Secondly, the Trimble Pro XR with a 12-channel receiver had the ability to receive real-time differential correction data. This is data collected at a base station at a known location, corrected, and retransmitted. This real time capability was more critical for other portions of the larger study giving researchers the ability to navigate in the field. The TDC2 data logger is dust and shock-proof as well as water-resistant. These are requirements for any fieldwork. The price of the Trimble was also within the given budget, approximately $10,000.

3.4 Mathematical Model

For each of the data sets described, detailed and shift-level data for both feller-bunchers and forwarder as well as GPS for the forwarder, a mathematical model will be created, five in all. Using regression analysis these models will predict production in one form or another for each machine.

Before regression models were created, F and t-tests were run on each of the significant variables in each data set to determine if there was a significant difference in the conditions each machine was working in. These F-tests tested for a difference in the variances between the two data sets being tested. The result of the F-test pointed to which form of the t-test that should be used. Significance in the form of a P-value is also presented along with the t-value.

Many of the variables used in these regression models are not continuous variables, as are distance and diameter. These other variables, such as operator and species, are represented as indicator variables. Indicator variables are equal to 1 if the variable is true and 0 if the variable is not true. They are "either/or" variables. To use indicator variables, a base case is chosen and indicator variables added for the other cases. There will always be one less indicator variable than total number of possibilities. Take species for example. The feller-buncher was observed cutting two different species, ponderosa pine and Douglas-fir. The majority of the time ponderosa pine was the observed species and so was set as the base case. One indicator variable was set for Douglas-fir. When "Douglas-fir" equals 1, the model predicts the time to cut one Douglas-fir stem and when "Douglas-fir" equals 0, the model predicts the time to cut one ponderosa pine stem.

4.0 Field Study Description

4.1 Study Site

The study site was located in the Blue Mountains of the Willowa-Wittman National Forest in northeastern Oregon, U.S.A.. Harvest units were approximately 20 miles north of the town of Enterprise, Oregon atop Robert's Ridge and Starvation Ridge (hence "Hungry Bob"). The harvest units studies for the Hungry Bob Fuels Reduction Study were a part of the larger Hungry Bob Timber Sale. This was a commercial sale and therefore not subsidized as some research sales are. All research harvest units were dominated by ponderosa pine with a Douglas-fir component. The harvest units had the characteristics shown in Table 4.1. "TPA" refers to the number of trees, or stems of merchantable size, per acre. "QMD" is the quadratic mean diameter of the stand, and is calculated as

$$d_q = \sqrt{((1/n)\Sigma d)}$$

"SDI" is the stand-density index and is a measure of density based on the number of trees per acre and the average diameter at breast height (Reineke, 1933). Stand-density index is calculated as

$$SDI = N\,(d_q/10)^{1.605}$$

"CC" is crown closure measured as the inverse of the amount of light reaching the forest floor. For example, if sunlight reaches 35% of the forest floor, then the crown closure is 65%.

Table 4.1 Hungry Bob study site characteristics

Unit	Vegetation Type	Unit Acres	Forested Acres	SDI	Basal Area (ft^2)	TPA	QMD (inches)	CC (%)
6	PSME/SYAL	76	69	196	106	223	9	58
7	PSME/SYAL	54	43	283	153	341	9	81
8	PIPO/SYAL	139	84	210	114	177	11	70
9	PSME/SYAL	134	80	190	107	190	10	65
10	PIPO/SYAL	88	55	181	105	181	10	60
11	PSME/SYAL & PIPO/SYAL	21	10	165	94	165	10	55
12	PSME/SYAL & PIPO/SYAL	28	14	182	106	182	10	60
22	PSME/SYAL	95	51	182	103	170	11	63
25	PSME/SYAL & PIPO/SYAL	5	3	165	94	165	10	55

PSME/SYAL - *Pseudotsuga menzeseii/Symphocarpus albus*
PIPO/SYAL - *Pinus ponderosa/Symphocarpus albus*

There was often great variation within each of the harvest units. Many of the units had portions that had been pre-commercially thinned in the past, leaving portions of the stand relatively open with some decaying stems on the forest floor. Dense patches of small diameter stems, averaging 3 to 4 inches in diameter dominated other portions of the stands. Despite this variation within each of the units, overall the units as a whole were relatively uniform in terms of timber size, density, and species composition. All units included non-timbered areas where the soil was too rocky and/or thin to support the growth of trees. This is the reason for the discrepancy found in Table 4.1 between unit acres and forested acres.

Units were also relatively uniform in terms of terrain. All units were located along ridge tops and average slope was considerably less than 35%, generally 5 to 15%. Some of the units had areas of steeper ground (34%-45%), but this occurred in isolated areas only.

4.2 Unit Layout

Prior to harvesting operations, unit boundaries were marked with tree tags as well as fluorescent orange "timber sale boundary" flagging. The decision was made on an individual unit basis whether the units would be marked as a leave tree or cut tree unit. This decision was made in favor of paint conservation, meaning if there were more trees to be cut than to leave, the unit was marked as a leave tree unit and vice versa. In leave tree units operators would cut all trees not marked to leave, in other words, cut all un-marked trees. In cut tree units operators were allowed to cut only those trees marked. Operators were also allowed to cut any tree within skidding corridors.

The Willowa-Whitman Ranger district had worked with the logging contractor, JayZee Logging of Enterprise, Oregon, on previous timber sales. The trust that had been built between the two organizations in the past carried over to the Hungry Bob timber sale. Skid trails were left up to the individual operators and did not need to be laid out on the ground and approved by the Forest Service timber sale administrator before harvesting in an area could begin. Feller-bunchers and forwarders used the same skid trail throughout the sale. This was the same for landing locations. This rapport between the Forest Service and the logging contractor greatly reduced the layout and approval delays that are often encountered on Forest Service timber sales when the approval of operational decisions are required.

Harvest units were located in a region that has historically been the site of intensive forest harvesting activities. This meant that all necessary roads were in place before harvesting began. In many instances old skid trails and landings were used, minimizing cumulative impacts.

The feller-buncher bucked all sawlogs to 16 feet and pulp into logs generally not longer than 20 feet. The forwarder would create decks along the side of haul loads to be later loaded onto log trucks using a standard loader. This meant that the majority of landings took up no more space than the travel way plus log lengths, requiring no landing construction.

Logging operations were instructed to stay out of non-timbered areas, except in case-by-case exceptions. This was true of deck locations as well.

4.3 Silvicultural Prescription

All units were marked with the same silvicultural goal in mind. This goal was to reduce the stocking density in order to promote stand health and growth. Increased stand health is instrumental in thwarting successful insect infestations, a widespread problem in this region. Trees with live crown ratios of greater than 30% were favored, as were site-appropriate species. In this case, ponderosa pine was favored over Douglas-fir, lodgepole pine, white fir, and grand fir.

Another silvicultural goal was to promote the growth of the large trees in order to speed the stand towards old growth characteristics. On the ground this meant leaving the larger dominant and co-dominates and removing the smaller intermediate and suppressed trees.

The third silvicultural goal was to promote the production of forage vegetation. All harvest units were also within grazed areas. Forage production is a byproduct of opening the stand up and allowing more sunlight to reach the forest floor.

Table 4.2 shows the before harvest and after harvest conditions on the units studied. A total of 15,786 tons were removed from the 409 total forested acres. Of this volume, 4207 tons or 26.6% was pulp, and 11580 tons or 73.4% was sawlog volume. This works out to a removal of 10.3 tons/acre of pulp and 28.3 tons/acre of sawlogs.

Table 4.2 Pre- and post-harvest stand conditions

Unit	Forested Acres	Pre-Harvest		Post-Harvest	
		TPA	QMD	TPA	QMD
6	69	223	9	81	13
7	43	341	9	64	13
8	84	177	11	54	14
9	80	190	10	61	14
10	55	181	10	67	13
11	10	165	10	77	12
12	14	182	10	72	12
22	51	170	11	48	15
25	3	165	10	77	12

4.4 Equipment Specifications

Two types of equipment were studied: feller-bunchers and forwarders. There was three of each machine working in research units, no two the same.

4.4.1 Feller-Bunchers

Three feller-bunchers were used to perform the felling and processing activities. The three machines were the Rottne SMV Rapid EGS, a quick Swedish-built machine, the John Deere 653E, a purpose-built feller-buncher with a Waratah HTH Warrior processing head, and the Caterpillar 320L excavator with a Keto 500 processing head. These three machines cover the spectrum of machines commonly found working in the woods today. These three machines have the specifications shown in Table 4.3.

Table 4.3 Feller-buncher equipment specifications

	Rottne SMV Rapid EGS	John Deere 653E	Caterpillar 320L Excavator
Horse Power	172	155	128
Operating Weight	30,203 lbs.	36,630 lbs.	50,490 lbs.
Carrier	6 WD, rubber tire, rear bogie axle, articulated	Tracked 9' 6"	Tracked 9' 9"
Max Travel Speed	15.5 mph	2.5 mph	3.4 mph
Max Boom Reach	32.8 ft.	23.5 ft.	34.9 ft.[1]
Min Boom Reach	0 ft.	9.75 ft.	10 ft.[2]
Tail Swing	N/A	0 ft.	4.1 ft.
Processing Head	EGS 600	Waratah HTH Warrior	Keto 500
Saw Capacity	23.6 in.	22.0 in.	29.5 in.
Delimbing Capacity	15.7 in.	16 in.	24.5 in.
Feeding Force	5,328 lbs.	10,620 lbs.	7,550 lbs.

[1] The boom on the Cat Exc. had been modified so maximum reach was less than this
[2] Again, the boom had been modified, so this is an approximation

Table 4.4 shows the number of days each feller-buncher worked in each unit.

Table 4.4 Days worked in each unit by each feller-buncher

	Unit									Total
	6	7	8	9	10	11	12	22	25	
Rottne SMV Rapid EGS	8	7		6						21
John Deere 653E	10	6		6	14			6	2	44
Caterpillar 320L Excavator			16	7		4	6	6		39
Total	18	13	16	19	14	4	6	12	2	104

The operators working for JZ Logging on the feller-bunchers were: Tom Zacharias, Rottne SMV Rapid EGS; Jim Adams, John Deere 653E; and Benny Gockley, Caterpillar 320L Excavator. Each was an experienced feller-buncher operator with at least three years of experience on their current machine. The next three figures show each of the three machines in a typical work environment.

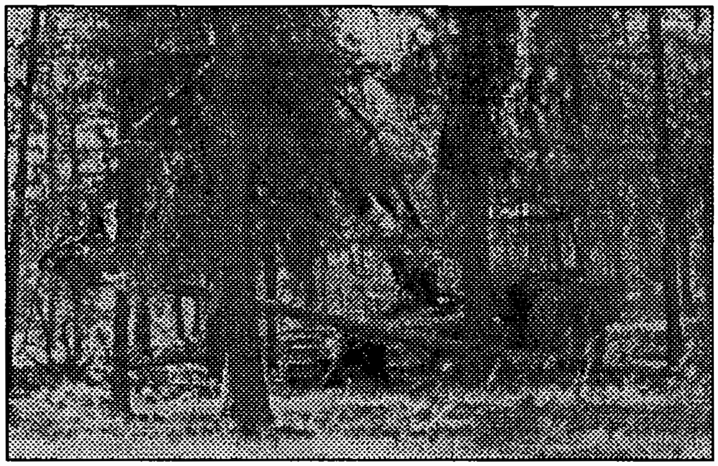

Figure 4.1 Rottne SMV Rapid EGS

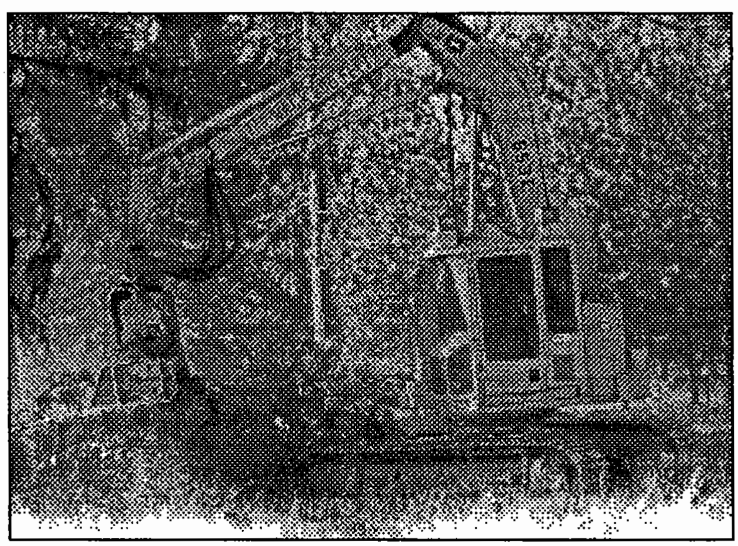

Figure 4.2 John Deere 653E

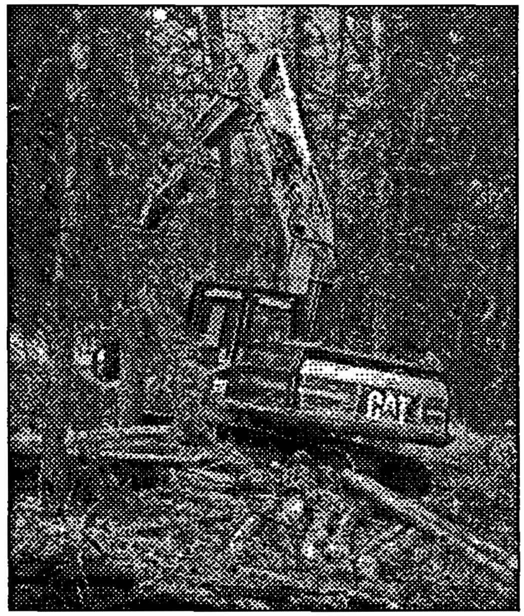

Figure 4.3 Caterpillar 320L Excavator

4.4.2 Forwarders

The three forwarders working on the Hungry Bob Timber sale were the Timbco TF815-C, the Rottne SMV Rapid, and the Rottne Rapid. Each have the specifications as described in Table 4.5.

Table 4.5 Forwarder equipment specifications

	Timbco TF815-C	Rottne SMV Rapid	Rottne Rapid
Horse Power	200	170	120
Machine Weight	30,203 lbs.	36,630 lbs.	50,490 lbs.
Capacity	16 tons	12 tons	10 tons
Carrier	8 WD, rubber tire, articulated	6 WD, rubber tire, articulated	6 WD, rubber tire, articulated
Bogie Axles	Front and Rear	Rear	Rear
Overall Length	30.3 ft.	31.4 ft.	28.9 ft.
Overall Width	9.4 ft.	9.1 ft.	8.7 ft.
Max Boom Reach	24.75 ft.	23 ft	22.7 ft.
Boom Location	On Cab	Behind Cab	Behind Cab

Table 4.6 shows the number of days each forwarder worked in each unit.

Table 4.6 Days worked in each unit by each forwarder

	Unit									Total
	6	7	8	9	10	11	12	22	25	
Timbco	7	6	14	6		2	3	5		43
Rottne SMV Rapid	9	7		6			1			23
Rottne Rapid[1]								5		5
Rottne Rapid[2]				7	15				1	23
Total	16	13	14	19	15	2	4	10	1	94

[1] Jim Zacharias
[2] Kelly Couch

The operators working for JZ Logging on the Forwarders were: Tim Wilcox, Timbco TF815-C; Jesse Shirley, Rottne SMV Rapid, and Jim Zacharias and Kelly Couch, Rottne Rapid. Time studies, detailed, shift, and GPS tracking, included only the first three operators, as they were all experienced with at least three years of experience. The fourth operator had run other equipment in the past, but was just starting on the forwarder. The next three figures show each of the three forwarders in typical working conditions.

Figure 4.4 Timbco TF 815-C

Figure 4.5 Rottne SMV Rapid

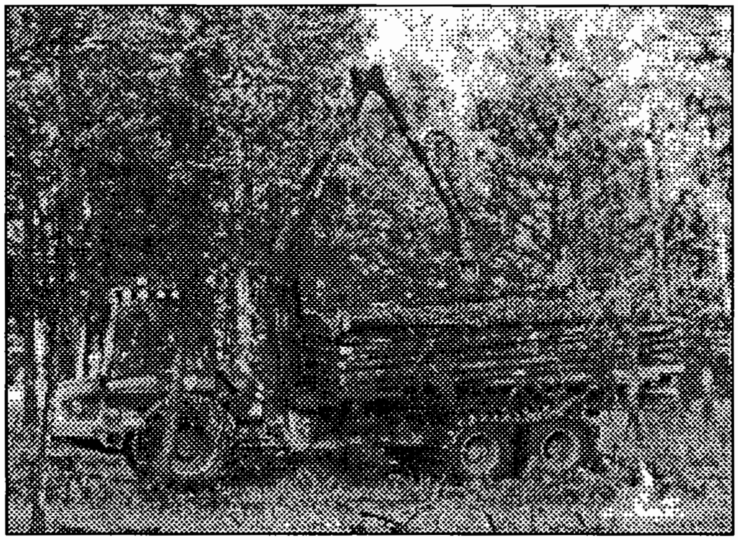

Figure 4.6 Rottne Rapid

4.4.3 GPS Units

The GPS units used for the Hungry Bob Harvesting Production Study had the specifications given in Table 4.7. Two units were used, one on each of the forwarders in units 22 and 6.

Table 4.7 GPS equipment specifications

Data Logger	TDC2
GPS Receiver	12 channel Pro XR
Antenna	Dome antenna with GPS/Real Time capabilities
Antenna mount	magnetic
Power Source	Adapter for cigarette lighter
Software	Pathfinder Office

Problems with the GPS units arose in unit 6,. Because of the data clarity problems associated with the placement of the antenna on the Timbco unit, we attempted to move the antenna to the top of the cab. The antenna was swept off the top of the cab, presumably by a branch, and run over by the machine on the first turn of the first day this new placement was tried. The operator was able to recover the many pieces of the antenna, but it was no longer in working condition. A replacement antenna was not received until after the field season. Also in unit 6, the GPS unit on the Rottne SMV Rapid was brushed off the top of the cab by a limb. In this case only the cord from the receiver to the antenna was damaged. This is a case where the part damaged was not an expensive part and a spare should have been on hand. Because a spare part was not available and a replacement cord was not received until after the field season, this was the end of GPS tracking of the forwarders.

4.5 Data Collection Methods

A combination of detailed time study, shift level time study, and GPS monitoring was used to gather data on production. Both the feller-bunchers and the forwarders were under the scrutiny of detailed and shift level time studies, while only the forwarder was monitored using GPS. The researcher carried out detailed time studies while the individual machine was being observed whereas the shift level time study consisted of forms each operator filled out at the end of each day.

4.5.1 Detailed Time Study

All of the machines involved in the harvesting of research units were studied using detailed time studies. This was accomplished using hand-held data recorders (Husky Hunters). The specific turn cycle was broken down into individual elements for the harvester and the forwarder.

4.5.2.1 Feller-Buncher

The per tree turn cycle for the feller-buncher was broken down into the following components:

Timed componants:

- Travel to the tree
- Cut and process the tree into log lengths

Delays:

- Maintenance
- Mechanical delay
- Personal delay
- Other delay

Variables:

- Tree diameter at the stump in inches
- Tree species, ponderosa pine or Douglas-fir
- Tree position, standing green, standing dead, or down dead
- Travel distance in feet

The following was also noted within each detailed time study file:

- Date
- Unit
- Start time
- Operator

A turn was designated by the cutting and processing of one tree and any other elements required to get that particular tree to the ground in log form. This included any movement to the tree as well as any delays. Travel time started when the feller-buncher releases the last tree and moves towards the next tree to cut. Travel time ends when the feller-buncher first grabs a tree. Cut times started when the feller-bunceher grabbed a tree with the processing head and continued until the final log was processed and dropped from the processing head or a delay occurred, whichever came first. This is also where the turn ended.

4.5.2.2 Forwarder

The turn cycle for the forwarder was broken down into the following elements:

Timed Events:

- Travel Unloaded
- Load
- Travel Loaded
- Unload

Delays:

- Maintenance delay
- Mechanical delay
- Personal delay
- Other

Variables:

- Number of pulp pieces loaded
- Number of sawlog pieces loaded
- Number of pulp pieces unloaded
- Number of sawlog pieces unloaded

The following was also noted within each detailed time study file:

- Date
- Unit
- Start time
- Operator

Turns were designated by one trip from the landing to the woods and back to the landing with a load. Therefore a series of loading times and travel loaded times occurred before the forwarder reached the landing to unload. Each turn also included the full decking time once the forwarder returned to the landing as well as any delays that occurred along the way. Travel unloaded started when the forwarder left the landing and ended when the forwarder stopped and began moving the grapple to grab the first logs. Load time began when the grapple first moved off the forwarder bunks and started towards a log and ended after the logs were placed on the bunks, properly situated, and the grapple was set to rest atop the load. During each reach to load the forwarder, the number of sawlogs and the number of pulp pieces was recorded. Travel loaded was the time it took to move to the next deck of logs. Unloading time was designated by the same activities as the loading time except that logs were being taken off the forwarder and placed in decks.

4.5.3 Shift Level Time Studies

At the end of each shift each operator filled out a shift report. This shift report contained information at the shift level on production for that particular shift.
Each form, no matter for which machine, contained the following items:

- Operator
- Unit
- Date
- Start time
- End Time
- Delays
    - Elapsed time
    - Type of delay (maintenance, mechanical, personal, other)
    - Reason for delay

4.5.3.1 Feller-Buncher

A sample of the feller-buncher shift-level report can be found in Appendix B. The feller-buncher shift-level reports asked for the following information in addition to the above:

- Total Pieces
    - Sawlog pieces
    - Pulp pieces
- Total Trees
    - Sawlog trees
    - Pulp trees

The computer within each harvester was able to give different information on production. Each operator was asked to give only that information which they were provided with. This posed some interesting challenges that are discussed later in section 5.1.1.1.

4.5.3.2 Forwarder

A sample of the forwarder shift-level report can be found in Appendix B. The forwarder shift-level reports asked for the following information in addition to the above:

- Number of loads for the day
- For each load, percent green volume on each load and if the load was sorted in the woods, at the landing, or both

The location of the sort turned out to be a moot point once the actual operation was observed. All loads were primarily sorted in the woods by the feller-buncher.

4.5.3 GPS Tracking

GPS units were mounted on the cabs of the forwarders in order to gain detailed cycle times and distances. As already shown in Table 4.7, two Trimble Pro XR GPS units were used for this purpose. Each unit consisted of a 12 channel Pro XR receiver, a TDC2 data logger, a dome antenna with a magnetic mount, and all the necessary cables. The antenna was mounted on the top of the cab on the Rottne units with the cable running in through preexisting holes in the top of the cab. For the Timbco forwarder, the antenna was placed atop the fuel tank with the cord running into the cab through the window behind the operator's head. The GPS units recorded times and positions at 10-second intervals throughout each turn during each day. The 10-second interval was chosen to reduce the amount of data records while still providing adequate data resolution.

4.6 Equipment Owning and Operating Costs

The first step in determine machine rates ($/SMH) was to call equipment dealers to find list prices for new pieces of the equipment used on the Hungry Bob Timber Sale. All prices are given in 1998 dollars. Data from Mechcost (Olsen, 1998) was used for determining operating costs. All factors and calculations used are detailed in Table 4.8 for the feller-bunchers and Table 4.9 for the forwarders.

Table 4.8 Feller-buncher machine costing

		Calculations	Rottne SMV Rapid EGS	John Deere 653E	Caterpillar 320L Excavator
a	List Price (including processing head)		$480,000	$428,000	$445,000
b	Life (years)		5	5	5
c	Hours/Year		1600	1600	1600
d	Life (hours)	b * c	8000	8000	8000
e	Salvage (%)		20%	20%	20%
f	Depreciation ($/SMH)	(a – a*e)/d	$48.00	$42.80	$44.50
g	AAI	((a-a*e)(b+1))/(2*b)+(a+e)	$326,400	$291,040	$302,600
h	Interest (%)		10%	10%	10%
i	Interest ($/SMH)	h*(g/c)	$20.34	$18.14	$18.86
j	Insurance and Tax		4%	4%	4%
k	I&T ($/SMH)	j * (g/c)	$8.16	$7.28	$7.57
l	**Owning Cost ($/SMH)**	f+i+k	**$76.50**	**$68.21**	**$70.92**
	Utilization		82%	82%	82%
n	Horse Power		172	155	128
o	Repair $ Maintenance		90%	90%	90%
p	Repair & Maintenance ($/SMH)	o*h*m	$35.42	$31.59	$32.84
q	Fuel (G/HP-HR)		0.02633	0.02633	0.02166
r	Fuel Cost ($/G)		$0.88	$0.88	$0.88
s	Lube (% of fuel)		37%	37%	37%
t	Fuel & Lube Cost ($/SMH)	q*n*r*(1+s)*m	$4.48	$4.03	$2.74
u	Operator Wage & Benefits ($/SMH)	35% benefits	$20.00	$20.00	$20.00
v	**Operating Cost ($/SMH)**	p+t+u	**$59.90**	**$55.62**	**$55.58**
w	**Total Costs ($/SMH)**	l+v	**$136.40**	**$123.83**	**$126.50**

Table 4.9 Forwarder machine costing

		Calculations	Timbco TF 815-C	Rottne SMV Rapid	Rottne Rapid
a	List Price (including processing head)		$318,000	$350,000	$300,000
b	Life (years)		5	5	5
c	Hours/Year		1600	1600	1600
d	Life (hours)	b * c	8000	8000	8000
e	Salvage (%)		20%	20%	20%
f	Depreciation ($/SMH)	(a – a*e)/d	$31.80	$35.00	$30.00
g	AAI	((a-a*e)(b+1))/(2*b)+(a+e)	$216,240	$238,000	$204,000
h	Interest (%)		10%	10%	10%
i	Interest ($/SMH)	h*(g/c)	$13.47	$14.83	$12.71
j	Insurance and Tax		4%	4%	4%
k	I&T ($/SMH)	j * (g/c)	$5.41	$5.95	$5.10
l	**Owning Cost ($/SMH)**	f+i+k	**$50.68**	**$55.78**	**$47.81**
	Utilization		86%	86%	86%
n	Horse Power		200	170	120
o	Repair $ Maintenance		100%	100%	100%
p	Repair & Maintenance ($/SMH)	o*h*m	$27.35	$30.10	$25.80
q	Fuel (G/HP-HR)		0.02488	0.02488	0.02488
r	Fuel Cost ($/G)		$0.88	$0.88	$0.88
s	Lube (% of fuel)		37%	37%	37%
t	Fuel & Lube Cost ($/SMH)	q*n*r*(1+s)*m	$5.16	$4.39	$3.10
u	Oporator Wage & Benefits ($/SMH)	35% benefits	$20.00	$20.00	$20.00
v	**Operating Cost ($/SMH)**	p+t+u	**$52.51**	**$54.49**	**$48.90**
w	**Total Costs ($/SMH)**	l+v	**$103.19**	**$110.27**	**$96.71**

Initial values are list prices given by equipment dealers. They do not include any rebates, incentives, or bartering.

The life of each machine is assumed to be five years. This is a standard value for these types of machines. There is a potential argument for extending the life of the rubber tired machines as compared to the tracked machines when working in rocky, thin soils such as were found on this timber sale. However, there is no hard evidence for this so all values were set equal.

The number of hours each machine will work each year is also set at a standard value for each of the machines. This value is based on working 8 hours a day, 5 days a week, 10 months a year.

A salvage value of 20% is a standard value assumed for nearly all logging equipment and heavy machinery. This is the percent of the initial value that an owner can expect to re-sell equipment for at the end of the specified life.

For this analysis straight line depreciation is assumed. This is the average drop in value each year the machine is owned. Depreciation is often misunderstood. It is a real loss in the value of a piece of equipment even though this amount is never actually paid out.

The average annual investment (AAI) is the average dollar value tied up in a machine.

The interest rate of 10% is a loan interest rate comparable to many lending rates offered by lending institutions.

Insurance and tax is an average figure that encompasses property tax paid on behalf of the machine as well as insurance required to operate the machine. Four percent is an average figure often used in machine rate calculations.

The owning cost is the sum of the depreciation, interest, insurance, and property tax figures. This cost is per scheduled machine hour and is incurred whether or not the machine is working.

The utilization rate used for both the feller-bunchers and the forwarders are taken from the large delays found during the shift-level time studies. Small delays, or those delays less than 10 minutes in duration, were not figured into this rate because the machine is generally left running during these times. An argument could be made that even though the machine is running, it is not running at full capacity so some utilization rate less than the large delays but greater than all delays should be used. It was felt that for this analysis, only using the large delay utilization rates was sufficient.

Repair and maintenance figures were taken from Mechcost (Olsen, 1998). The repair and maintenance is figured as a percentage of depreciation and adjusted for utilization. It includes undercarriage track or tire costs. Each machine as well as organization will have a different repair and maintenance rate. Because actual costs were not available, an average was used which was equal across all machines.

Fuel consumption rates are also averages based on the horsepower of the particular equipment. These figures are also taken from Mechcost (Olsen, 1998). The fuel cost of $0.88 per gallon is an average off-highway diesel cost as observed in the area at the time of the field study. Total fuel costs are figured by multiplying the horsepower of the machine by the gallons per horsepower-hour consumption rate and by the cost of fuel. Lube costs are added to this figure and are assumed to be 37% of fuel costs. This rate is also a standard machine costing assumption. The total fuel and lube costs are adjusted for scheduled machine hour by multiplying by the large delay utilization rate.

Operators wages are taken from the 1998 Annual Wage Survey by the Associated Oregon Loggers. This study averaged wages by occupation across many regions of the state but provided no averages for both feller-buncher and forwarder operators in northeast Oregon, therefore the statewide average was used. This statewide average was $15.00/hour for the feller-buncher and $15.10/hour for the forwarder. Benefits were assumed to be an additional 35% of the hourly wage. These benefits include workers compensation and social security. Because there is such variation in the workers compensation rates charged, both wage plus benefit hourly rates were rounded to $20/hour.

Operating costs are all those costs that are incurred only when the machine is in the field working. These include repair and maintenance, fuel and lube, and operator wage and benefits. These costs have been adjusted for large delays.

The total hourly machine rate is the sum of the owning and operating costs. This is the value which is used in all calculations of $/ton. An important point to remember is that these figures will be different for every machine and every operator. The calculations presented here are theoretical and used for comparison purposes only.

5.0 Analysis and Results

5.1 Analysis Methods

5.1.1 Shift-level Data

All shift report information was entered into Excel spreadsheets. Data were checked for errors and outliers. Outliers were removed from the data sets that would be used later for model creation. These outliers were days when one unit was completed and the next started. On these days, there were often only 2 to 3 hours of productive time in each unit. Over such short periods of time a larger variance in production was found as compared to a full day. A large enough data set for both the feller-bunchers and forwarders existed so that these outliers were simply removed from the data set, leaving a sufficiently large data set behind.

5.1.1.1 Feller-Buncher

One problem encountered with the feller-buncher daily production values was that there was not a consistent measure of production common to all three machines. The following information was available from each machine:

Table 5.1 Shift-level data available from each feller-buncher

	Total Pieces	Sawlog Pieces	Pulp Pieces	Total Trees	Observations
Rottne SMV Rapid EGS		X		X	21 (20.0%)
John Deere 653E	X	X	X		45 (42.9%)
Caterpillar 320L	X			X	39 (37.1%)

Total pieces was the logical variable to use to measure daily production. In order to predict total pieces for the Rottne, the following relationship between total pieces and sawlog pieces was determined from the 45 observations from the John Deere, the only machine which was able to report both total pieces and sawlog pieces:

$$\text{Total pieces} = 5.4067 * (\text{sawlog pieces})^{0.8317}$$

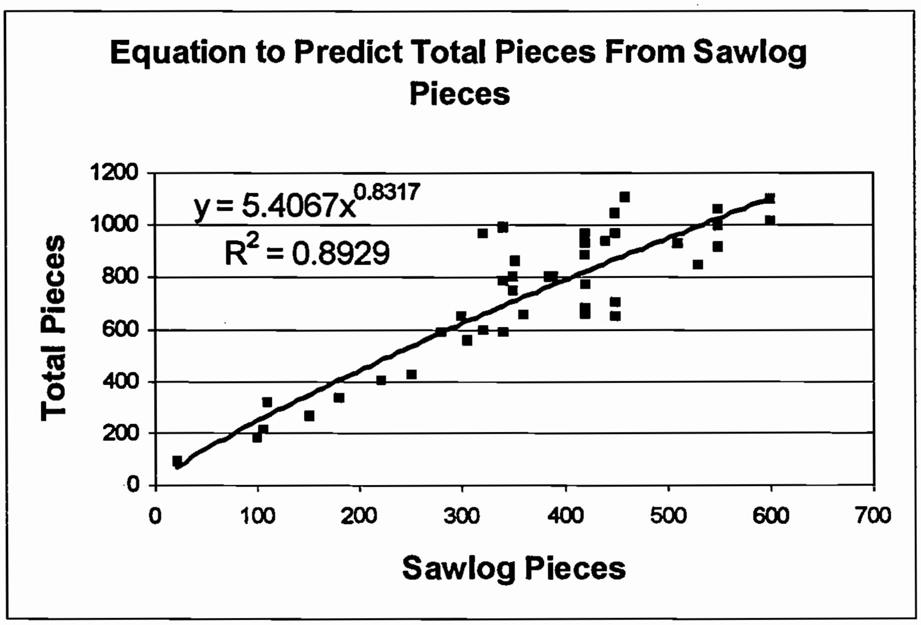

Figure 5.1 Relationship between sawlog pieces and total pieces

For example, on a day when the Rottne produced 469 sawlog pieces:

$$\text{Total pieces} = 5.4067 * (469)^{0.8317}$$

$$\text{Total pieces} = 901$$

It was now possible to compute pieces per scheduled machine hour (pieces/SMH) as well as pieces per productive machine hour (pieces/PMH). Another variable created at this stage was utilization, where:

Utilization = PMH/SMH

Or

$$\text{Utilization} = 1 - (\text{Total Delay \% /SMH})$$

This utilization rate is used to adjust harvester production for large delays, or those delays longer than 10 minutes in duration.

Data was checked for trends through time by plotting average pieces/PMH against the date. A trendline was added and no trends were found, meaning there was no apparent learning curve. However, there was a significant drop in production after the crew returned in October. This drop in production coupled with the fact that no detailed

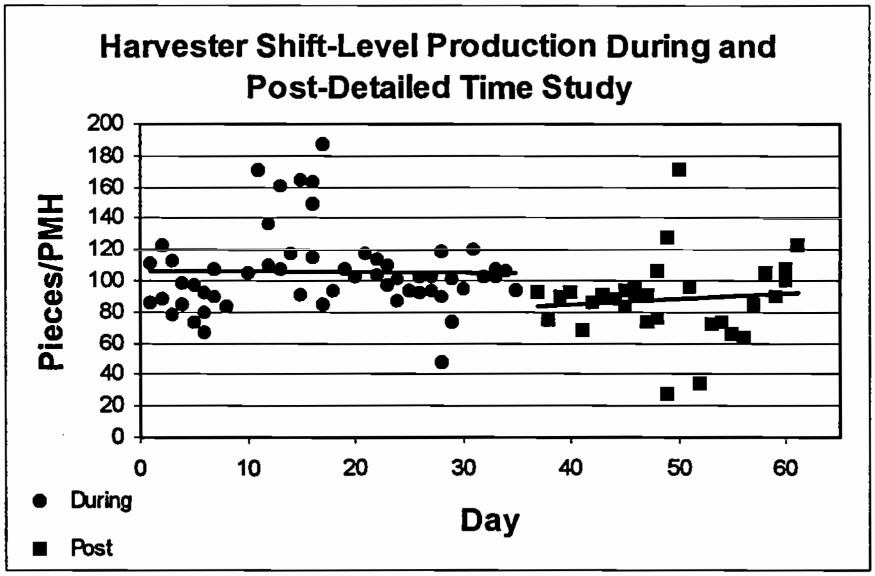

Figure 5.2 Harvester shift-level production during and after detailed time study

data was taken at this time meant that all data from this second stint was excluded from further analysis. The reason for this drop in production is unclear. There were no changes in operators or machines. The weather was cooler but no precipitation occurred. One possible explanation for this drop in production is that there were no detailed time studies taking place. The operators were all quite competitive and may have increased production when they knew they were being watched. Once they knew there was no researcher with a stopwatch watching them, they may have relaxed a bit. This post-detailed time study shift-level data may actually be more representative of typical harvesting operations because of this reason. However, because there is no detailed or GPS data for this same time period, it was excluded from further analysis.

5.1.1.2 Forwarder

Percent sawlog load compositions were averaged and multiplied by the total number of loads for the day. This gave the number of pure sawlogs for the day. This number was then subtracted from the total number of loads for the day in order to get the total number of pure pulp loads for the day. These two numbers, total pure sawlog loads and total pure pulp loads, were used in the determination of volume.

Forwarder production data was also checked for trends through time by plotting loads/SMH against the date, as seen in Figure 5.3. No trends were found for the original

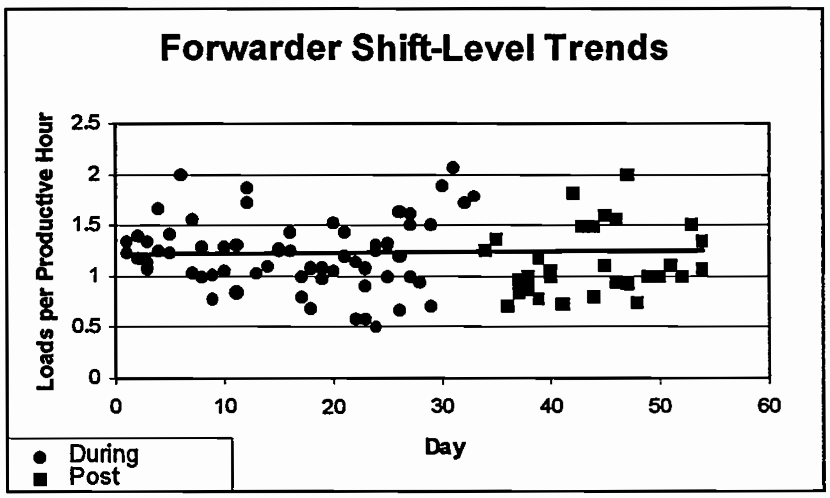

Figure 5.3 Forwarder shift-level production during and after detailed time study

three machines prior to the break. Like the feller-buncher, a significant drop in production occurred when the crew returned in October. This data was excluded from further analysis. As expected, a trend was detected for the new operator on the Rottne Rapid. Because of this learning curve his data was excluded from further analysis.

5.1.2 Detailed Data

Detailed time study data was downloaded from the Husky Hunter data collector in the field and stored as data files. Once back in the office, data files were converted to Excel spreadsheets for further analysis.

5.1.2.1 Feller-Buncher

The first step in data analysis of detailed time study data was to identify outliers and remove those observations. A total of over 2250 observations were taken on the three harvesters, so removing a few outliers did not cause problems with sample sizes.

A correlation was run to test for multicolinearity between variables as well as to determine the relative strength of individual variables. From Table 5.2 it can be seen that the strongest relationships with cycle time are diameter and distances. These are the two variables that will be looked at most closely. Also, no multicolinearity can be seen between variables.

Table 5.2 Feller-buncher correlation matrix

	standing	down	spp	diam	dist	slope	cycle time
standing	1.000						
down	-0.020	1.000					
spp	0.115	0.054	1.000				
diam	-0.135	0.069	-0.088	1.000			
dist	-0.012	-0.004	-0.006	0.065	1.000		
slope	-0.028	-0.011	-0.126	0.022	0.010	1.000	
cycle time	-0.107	-0.006	0.026	0.389	0.718	-0.035	1.000

5.1.2.1.1 Time Trend

Sequential numbers were assigned to the date which each data file was taken. In order to determine if a trend existed, productive cycle time was plotted against the sequential day variable for each operator and a trendline fit to each data set. No time trend was found for any of the feller-bunchers.

5.1.2.1.2 Diameter Distribution

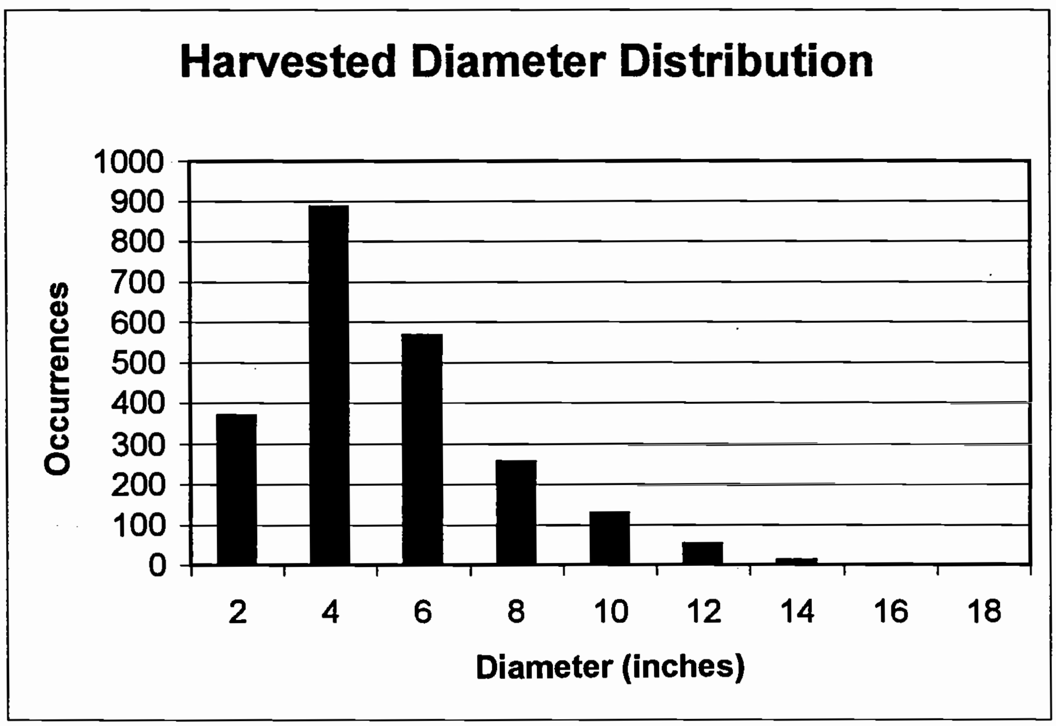

Figure 5.4 Diameter distribution from detailed time study data

Diameter distributions were checked for each of the three operators, both to ensure an adequate distribution for subsequent models and to determine if any differences in conditions existed between operators. Figure 5.4 shows an adequate diameter distribution with the following characteristics:

Table 5.3 Characteristics of diameter distribution

	Rottne	John Deere	Cat Exc.	Overall
N	670	1059	538	2267
Mean	7.8090	6.6308	7.3383	7.1469
Minimum	2	2	2	2
Maximum	16	16	20	16
Standard Deviation	2.4156	2.4921	2.6364	2.5558

F and t-tests were run between all operators to determine if these diameter differences were statistically significant. The F-test looked at the variances between the two data sets. The results of this test determined which t-test should be used. As can be seen in Table 5.4, the diameters observed for each of the three machines are all statistically different. This means that in order to fairly look at production differences between the three machines, observed machine averages are not adequate, and predictions using an overall average is required.

Table 5.4 Diameter t-test results

	F	t	Significance	Different?
Cat Exc. – John Deere	6.650	5.162	0.000	Yes
Cat Exc. – Rottne	9.652	-3.200	0.001	Yes
John Deere – Rottne	0.662	-9.760	0.000	Yes

5.1.2.1.3 Move Distance

The distance traveled between trees was looked at in the same manner the diameter distributions were treated. First, distance was plotted against move time and all outliers were removed (Figure 5.5).

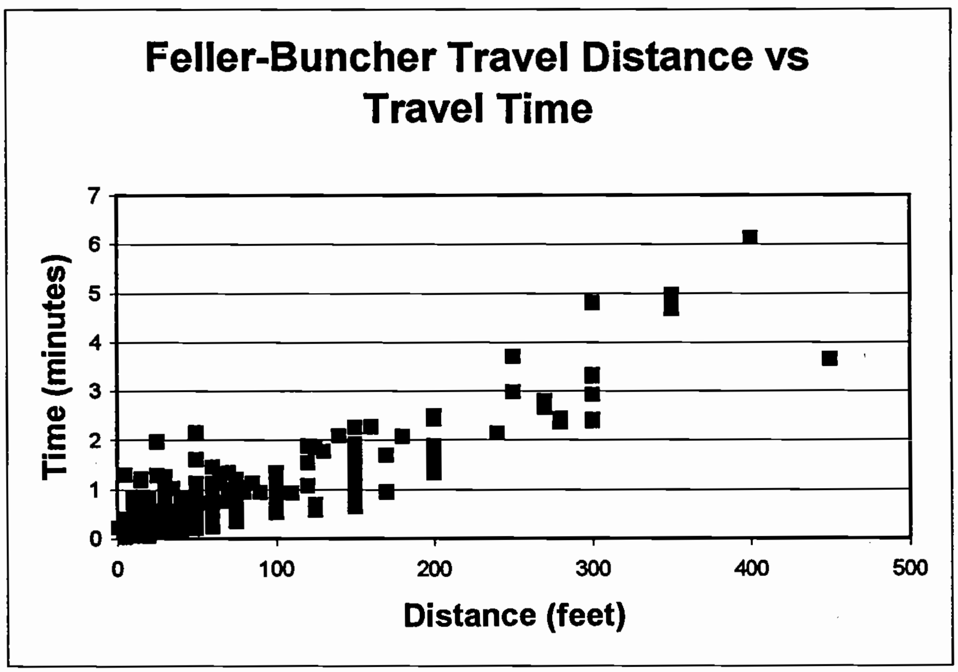

Figure 5.5 Feller-buncher travel time vs. travel distance

Mean travel distance was computed for each operator to determine if any difference could be detected in the conditions in which each of the machines operated. These results can be seen in Table 5.5.

Table 5.5 Characteristics of travel distances

	Rottne	John Deere	Cat Exc.	Overall
N	670	1059	538	2267
Mean	14.2537	14.0670	13.4108	13.9665
Minimum	0	0	0	0
Maximum	450	300	200	450
Standard Deviation	43.6134	28.8271	26.9030	33.4842

Again, F- and t-tests were run to test for differences in the variance and average move distances between machines. The results of these tests, shown in Table 5.5, are that there was no statistically significant difference in move distances.

Table 5.6 Distance t-test results

	F	t	Significance	Different?
Cat Exc. – John Deere	0.066	-0.440	0.660	No
Cat Exc. – Rottne	0.188	-0.329	0.695	No
John Deere – Rottne	0.556	-0.107	0.915	No

5.1.2.2 Forwarder

The forwarder was looked at in much same way as the harvester. A correlation matrix was run to find any multicolinearity between variables as well as relative correlation to total cycle time. The three variables showing the strongest relationship with cycle time are the number of stops made by the forwarder (r=0.743), distance traveled (r=0.466), and the number of pieces per load (r=0.554). These are the three variables that will be looked at the closest. Strong multicolinearity (r=0.870) exists between the number of pieces per load and the number of stops required to make a full load. This relationship is explored further when regression analysis is completed. Because of this strong relationship between the pieces and stops, only one can be used in the resulting production models. As can be seen in section 5.2.1.1, the number of pieces in a load drops out and only the number of stops is retained.

Table 5.7 Forwarder correlation matrix

	Stops	*Distance*	*Pieces*	*Cycle Time*
Stops	1.000			
Distance	0.129	1.000		
Pieces	0.870	-0.038	1.000	
Cycle Time	0.743	0.466	0.554	1.000

5.1.2.2.1 Time Trend

Forwarder data was also looked at for a trend across time. This was accomplished by plotting cycle times against the day on which they were observed (Figure 5.5).

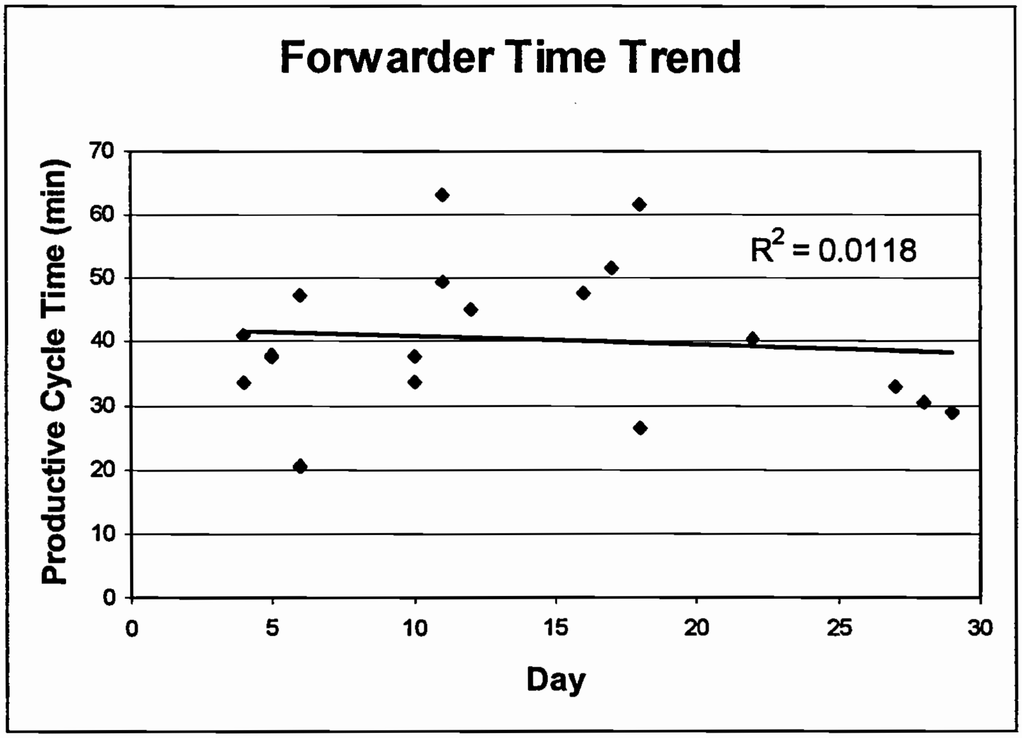

Figure 5.5 Forwarder time trend

A slight trend does appear when a trendline is fit to the data. However, the combination of only 19 data points and a low R^2 make this trend unreliable.

5.1.2.2.2 Distance

Distance was not taken during detailed time studies, but was instead taken directly from GPS data when the detailed cycle recorded could be matched to a GPS cycle. For those cycles that did not have correlating GPS files, distance was estimated from GPS data. Distance was plotted against total cycle time to be sure no outliers were present. If an outlier had been present, careful consideration would have gone into the treatment of the individual record. With only 19 full records, the loss of one could not be afforded. Fortunately, no outliers were found which required any action.

The distance distribution has the following characteristics:

Table 5.8 Distance distribution statistics

	Timbco	Rottne Rapid SMV	Rottne Rapid	Overall
N	8	8	3	19
Mean	1792	2074	2372	2002
Minimum	1330	990	1816	990
Maximum	2812	2890	3090	3090
Standard Deviation	490.8	650.4	277.8	591.8

Due to small sample sizes and high variability in cycle times, no statistical difference could be found between the three machines. Therefore, the difference in travel distance between operators was not an issue.

5.1.2.2.3 Stops

The variable "stops" refers to the number of times the forwarder stopped to pick up logs. The number of times an operator stopped was positively correlated with the total productive cycle time.

The distribution of number of observed stops had the following characteristics:

Table 5.9 Number of stops distribution statistics

	Timbco	Rottne Rapid SMV	Rottne Rapid	Overall
N	8	8	3	19
Mean	58.8	74.0	52.7	64.2
Minimum	40	44	52	40
Maximum	73	115	54	115
Standard Deviation	10.62	21.6	1.2	17.4

As with distance, because there was no statistical difference between operators, the difference in number of stops was not an issue.

5.1.2.2.4 Number of Pieces

The variable "pieces" refers to the total number of pieces on a forwarder load. The total number of pieces was broken down into the number of pulp pieces and the number of sawlogs.

The distribution of the number of pieces had the following characteristics:

Table 5.10 Number of pieces distribution statistics

	Timbco	Rottne Rapid SMV	Rottne Rapid	Overall
N	8	8	3	19
Mean	91.1	111.1	72.8	96.7
Minimum	53	61	55	53
Maximum	149	192	93	192
Standard Deviation	27.9	41.5	19.3	34.9

5.1.3 GPS Data

GPS data was recorded for all of unit 22 and approximately half of unit 6 due to mechanical failures. Data from the GPS units were stored until the field season was completed. Back in the office, the data were differentially corrected from the Portland State University base station. Differential correction removes much of the error from the GPS positions recorded in the field. This is accomplished by calculating the error of the individual signals from each satellite as received at a known base station and applying these corrections to the data recorded in the field. The Portland State base station was not the base station closest to the study site geographically, but it was the closest base station from which files could be gathered. Some of the data gathered in the field by the GPS units were real time. "Real time" data refers to data received at a base station, differentially corrected, and the correction for each signal sent from each satellite re-transmitted over radio frequencies. Real time data is much more desirable than uncorrected data when navigation in the field is required, but did not have much use in this application. Once differential corrections had been made, each file was analyzed by following each point taken sequentially through time. In this manor, the number of stops, total cycle time, and cycle distance was recorded. An average day's worth of data looked like Figure 5.5.

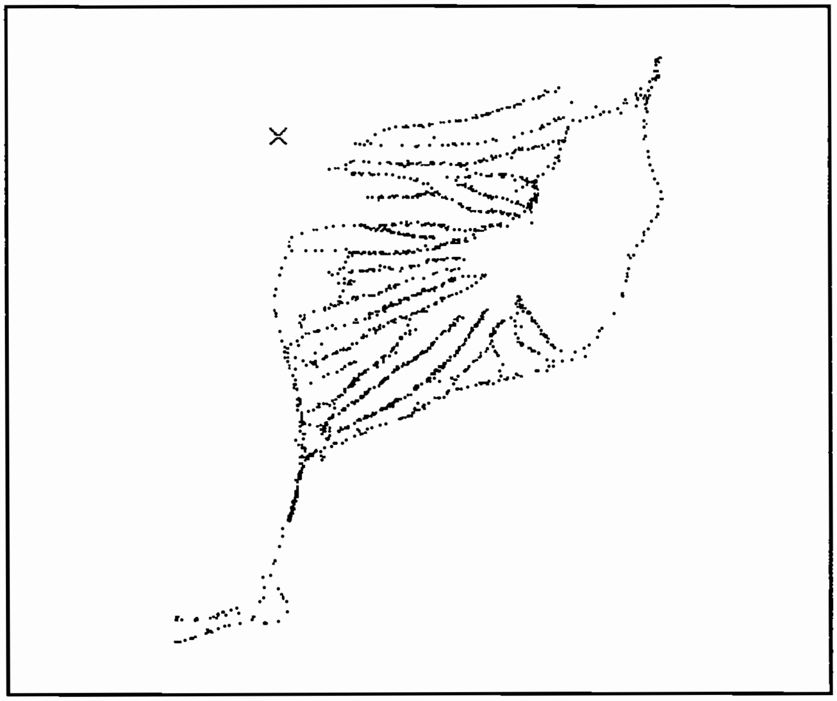

Figure 5.6 Sample GPS file spanning one work day

The data shown in Figure 5.6 were recorded in Unit 6 by the Rottne SMV Rapid. The data files recorded by the Timbco had much less defined trails because of the placement of the antenna on the machine. The cab blocked out many of the satellites and the boom compounded the problem. What was happening is termed "multi-pathing". Multi-pathing occurs when the satellite signal bounces off objects such as rocks, foliage, or the cab of the forwarder. This bouncing signal, once received by the GPS, creates an error in the position recorded. Unpublished research by Stephen Reutebuch (Reutebuch, 1999) tracking forest machinery using GPS on the Blue Ridge Harvesting Options Study during the summer of 1998 detected these same obstacles to clear signals. This meant that a number of the data files for the Timbco could not be used.

When comparing GPS data to detailed data from the same turn, the number of stops detected from the GPS data was approximately half to the number observed during the detailed time studies. A stop was recorded when the forwarder was in a single position for at least two data points, or 20 seconds. The variable number of stops is therefore rendered useless for the purpose of validating detailed time study models. However, distance-time relationships were useful in filling in gaps in detailed-time study information. The following relationship was used to predict travel distance:

$$\text{Distance} = 0.41841(\text{Productive Cycle Time} - \text{Decking Time}) + 522.63$$

This relationship fit the GPS data with an R^2 of 0.4459.

The range of distances observed with GPS is as shown in Table 5.11.

Table 5.11 GPS distance statistics

	Timbco	Rottne Rapid SMV	Rottne Rapid	Overall
N	24	35	26	85
Mean	1887.5	2219.5	2073.1	2081.0
Minimum	1100	1000	1100	1000
Maximum	2600	3900	3100	3900
Standard Deviation	373.4	698.3	693.1	630.3

5.1.4 Volume Data

The loader operator filled out shift-level time sheets like those the other operators filled out. The shift forms included start time, end time, truck load ticket numbers, and the unit number. These shift forms were not used in this analysis, however. All logs were cold decked and the loader often needed to take logs from more than one deck in order to make a full truckload. This meant it was improbable to determine which forwarder loads went onto which truckload. This could have been accomplished using paint, brands, or other forms of marking individual forwarder loads, but would have taken much too much effort on the part of the researcher for the value that would have been gained. Instead a summary of pulp tons and sawlog tons for each unit was obtained from the Forest Service. This summary is shown in Table 5.12.

Table 5.12 Tons removed per unit

Unit	Sawlogs			Pulp		
	Forwarder Loads	Tons	Tons per Load	Forwarder Loads	Tons	Tons per Load
6	94.9	942.36	9.93	50.1	591.67	11.82
7	83.8	845.3	10.09	29.2	414.43	14.19
8	112.2	1637.01	14.59	38.8	467.79	12.06
9	125.9	1534.54	12.19	30.1	392.92	14.03
10	95.4	1081.77	11.34	30.6	322.23	10.53
11	27.4	442.3	16.14	9.6	108.54	11.31
12	35.7	640.18	17.93	16.3	221.32	13.58
22	63.0	660.43	10.48	42.0	333.02	7.93
25	5.4	63.09	11.68	-	-	-

Joseph Timber Company sample scaled a portion of the sawlog loads coming into the mill and made this information available to researchers as well as the Forest Service. From these two sources, average weights per log and per forwarder load was able to be determined.

Table 5.13 Average log weights

	Pounds per Piece	Tons per Piece
Ponderosa pine Sawlog	406.764	0.203382
Douglas-fir Sawlog	301.682	0.150841
Sawlog average	375.240	0.187620
Pulp	227.408	0.113704
Average piece	319.832	0.159916

All logs were short logs, meaning an average sawlog length of 16 feet and an average pulp log length of approximately 20 feet. Sawlog weights were taken from the scaling information provided by Joseph Timber Company. The average sawlog weight is a weighted average based on species composition averages from the detailed harvester data and assumed to be 70% ponderosa pine and 30% Douglas-fir. The average piece weight is a weighted average based on the ratio of total tons of pulp and sawlogs. This ratio was 63% sawlog to 37% pulp by weight.

In order to derive an average weight per tree, a height to diameter ratio was determined using cruise data from before and after harvesting. From this relationship the height at each diameter could be estimated and therefore the number of logs, both sawlogs and pulp logs, could be estimated. Applying the average log weights from Table 5.13, the average tree was assumed to produce 0.306958 tons of merchantable wood.

From the forwarder shift forms, the total number of pulp and sawlog forwarder loads from each unit was known. The total tons the mills received for both sawlogs and pulp was also known. From this, the average weight per forwarder load could be determined. A t-test was run to determine if there was any statistically significant difference between the average weight of a sawlog forwarder load and a pulp forwarder load. No statistical difference was found. Therefore the average forwarder load, no matter the composition, was assumed to be 12.3 tons.

5.2 Results

5.2.1 Feller-Buncher

5.2.1.1 Production Models

From the shift-level data, feller-buncher production can be predicted using the model presented below. This predicts the average production that can be expected in similar situations. This model is taken from the shift forms spanning the same time as the detailed time studies. No validation was preformed for this model.

Pieces per Hour = 147.5220 – 43.4527 (John Deere) – 53.8326 (Cat Exc.)

Where:

John Deere = binary indicator variable, 1 = John Deere, 0 = other

Cat Exc. = binary indicator variable, 1 = Cat Exc., 0 = other

This model is valid for the conditions listed in Tables 5.3 and 5.5 and has the following characteristics:

Table 5.14 Statistics for dependent and independent variables used in shift-level feller-buncher production model

Dependant Variable	Parameter	Coefficient	Standard Error	t statistic	P Value	Adjusted R^2
Pieces per Productive Hour			3.238			0.401
	Intercept	147.5220				
	John Deere	-43.4527	7.765	-5.596	0.000	
	Cat Exc.	-53.8326	8.119	-6.631	0.000	

This regression shows that as compared to the Rottne, the John Deere produced an average of 43.5 fewer pieces per hour and the Cat Exc. produced an average of 53.8 fewer pieces per hour.

Production can also be estimated from detailed time study data. The model shown below predicts the time in minutes to harvest one tree. This model was validated using a random sample of 50 observations that were not used to create the model.

$$\text{Cycle Time} = 0.0293 + 0.2170\,(\text{JD}) + 0.3500\,(\text{CE}) - 0.1412\,(\text{sd}) - 0.2582\,(\text{dd}) + 0.0257\,(\text{diam}) + 0.0031\,(\text{diam}^2) + 0.0108\,(\text{dist}) + 0.0544\,(\text{spp})$$

Where:

JD = binary indicator variable, 1 = John Deere, 0 = other

CE = binary indicator variable, 1 = Cat Exc., 0 = other

sd = binary indicator variable, 1 = standing dead tree, 0 = other

dd = binary indicator variable, 1 = down dead tree, 0 = other tree

diam = diameter, in inches, at base of tree

dist = distance traveled

spp = binary indicator variable, 0 = ponderosa pine, 1 = Douglas-fir

This model is also valid for the conditions listed in Tables 5.3 and 5.5 and has the following characteristics:

Table 5.15 Statistics for dependent and independent variables used in detailed feller-buncher production model

Dependant Variable	Parameter	Coefficient	Standard Error	t statistic	P Value	Adjusted R^2
Minutes per tree			0.006			0.708
	Intercept	0.0293				
	JD	0.2170	0.015	14.863	0.000	
	CE	0.3500	0.017	20.903	0.000	
	Sd	-0.1412	0.028	-5.067	0.000	
	Dd	-0.2582	0.070	-3.671	0.000	
	Diam	0.0257	0.010	2.468	0.014	
	$diam^2$	0.0031	0.001	4.964	0.000	
	Dist	0.0108	0.000	60.489	0.000	
	Spp	0.0544	0.013	4.074	0.000	

Both the shift-level model and the detailed model show that the John Deere and the Cat Exc. are slower than the Rottne. This model also shows that dead material, whether standing or down, takes less time to process than does green trees. This is due primarily to the fact that dead, dry branches are more brittle and easier to remove than green branches and so less time is spent de-limbing. As diameter and distance increase, so does the cycle time. Finally, this model shows that Douglas-fir stems take longer to process than do ponderosa pine stems.

As mentioned before, this model was validated using a random sample of 50 observations not included in the data set used to create the model. The results of the paired t-test are shown in Table 5.16. For a sample of this size, the critical t-statistic at which the two means would be considered statistically different is 1.960. Therefore, the null hypothesis that the actual cycle time and predicted cycle time are not statistically different is accepted.

Table 5.16 Paired t-test for detailed harvester production model

	Actual Cycle Time	Predicted Cycle Time	Difference
Mean (minutes)	0.6696	0.6888	0.0192
Variance	0.0951	0.1036	
Observations	50	50	
Pearson Correlation	0.8105		
t Statistic	-0.6977		

An important note is these two regression equations are predicting two different measures of production. The shift-level model is predicting the total number of pieces, both sawlog and pulp pieces, which can be produced in an hour. The detailed model predicts the time in minutes it takes to cut and process one tree. This one tree may contain many pieces, depending on the size and quality of the tree. Therefore there is not a direct comparison between production estimates until both are corrected for delays and converted to a common unit, such as tons per scheduled machine hour.

5.2.1.2 Utilization Rates

Utilization rates taken from both the detailed and shift-level time studies are needed to correct for delays. For both the detailed and shift-level studies delays were tested for statistical differences between machines. In no case were delays found to be different. Therefore, a common utilization rate was used for both the small delays, less than 10 minutes, and large delays, longer than 10 minutes. Utilization rates for small delays come from the detailed data. These small delays are already embedded in the production estimates from the shift-level data. The observed utilization rates for the feller-buncher are as shown in Figure 5.17. The production prediction taken from the detailed time data is truly delay free and both small and large delays must be corrected for. The production estimate taken from the shift-level data has small delays already imbedded, so only needs to be adjusted for large delays.

Table 5.17 Small and large delay utilization rates for the feller-buncher

	Small Delay Utilization Rate (< 10 minutes)	Large Delay Utilization Rate (> 10 minutes)
Detailed Time Study	7 %	
Shift-level Time Study		18%

5.2.1.3 Production Comparisons

Average conditions were assumed for all three feller-bunchers and used in the production models presented in 5.2.1.1. Average conditions were assumed for each machine. These conditions were an average diameter of 7.1 inches, a travel distance of 14 feet, and average species composition of 30% Doulgas-fir and 70% ponderosa pine, and a standing green stem. Production estimates from the detailed time study data were adjusted for both small and large delays. Production estimates from the shift-level time study data were adjusted for large delays only. All estimates were then converted to $/ton. These figures are presented in Table 5.18.

Table 5.18 Production estimates for the feller-buncher across average conditions

	Detailed (min/turn)	Detailed (tons/PMH)	Scheduled $/ton	Shift (turns/PMH)	Shift (tons/PMH)	Scheduled $/ton
Adjusted R^2	0.709			0.401		
S_x	0.006026			3.16999597		
Rottne	0.535464	34.395352	$ 5.20	147.521954	23.5911208	$ 7.05
John Deere	0.75245	24.476669	$ 6.63	104.069286	16.642344	$ 9.07
Cat Exc.	0.885446	20.800234	$ 7.97	93.6893122	14.98242	$ 11.10

The relationships between Rottne and John Deere and John Deere and Cat Exc. production remain constant from the detailed to the shift-level estimates. For all machines, the detailed estimates are approximately 73% of the shift-level estimates.

Applying the standard error of the mean of each model to the production estimates, an idea of the relative accuracy of each model can be gained. This information is presented in Table 5.19 and Figure 5.7 for the estimates derived from the detailed data and Table 5.20 and Figure 5.8 for the estimates derived from the shift-level data.

Table 5.19 Relative confidence of feller-buncher detailed production estimates at 95% confidence

	Rottne	John Deere	Cat Exc.
Lower Limit	$5.14	$6.58	$7.92
Average	$5.20	$6.63	$7.97
Upper Limit	$5.26	$6.69	$8.03

Table 5.20 Relative confidence of feller-buncher shift-level production estimates at 95% confidence

	Rottne	John Deere	Cat Exc.
Lower Limit	$6.90	$8.81	$10.74
Average	$7.05	$9.07	$11.10
Upper Limit	$7.21	$9.36	$11.49

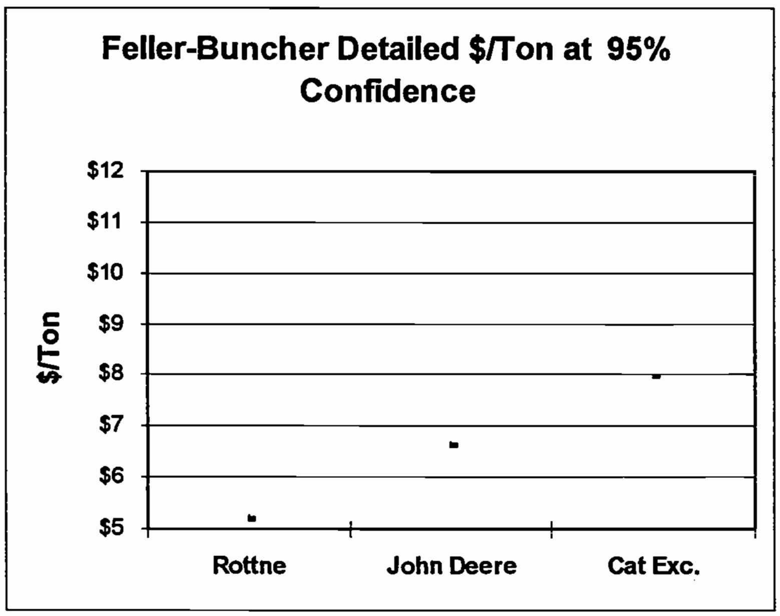

Figure 5.7 Relative confidence of feller-buncher detailed production estimates at 95% confidence

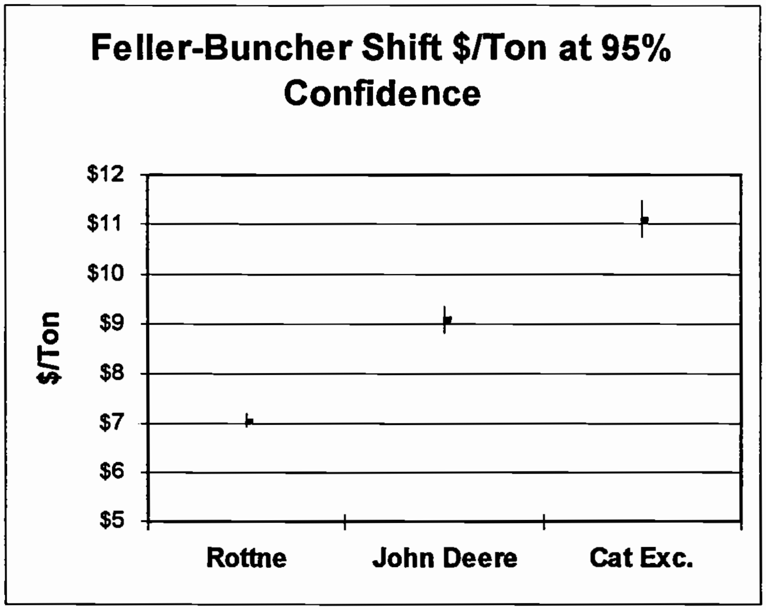

Figure 5.8 Relative confidence of feller-buncher shift-level production estimates at 95% confidence

The range of estimates from the detailed models is $0.11/ton for the Rottne and $0.10/ton for the John Deere and Cat Excavator. The range of estimates from the shift-level model is $0.29/ton for the Rottne, $0.59/ton for the John Deere, and $0.73/ton for the Cat Excavator. As can be seen in Figure 5.9 the estimates from the shift-level and detailed estimates are statistically different. A t-test was conducted to verify this.

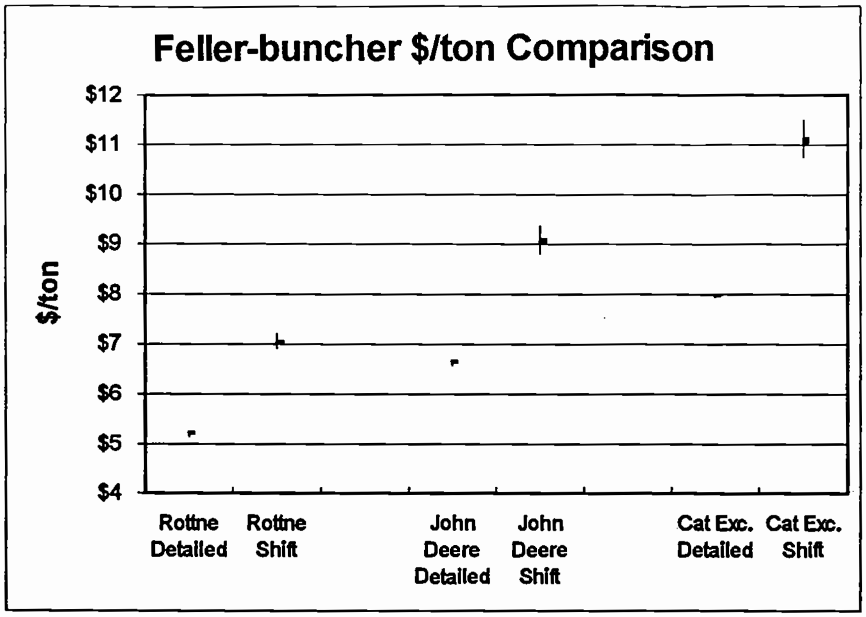

Figure 5.9 Comparison of feller-buncher shift and detailed estimates of $/ton

One possible explanation for the discrepancy between models is the same reason there was a drop in production after the crew returned in October. Operators knew when a researcher was watching them and wanted their production to be as high as possible. This would suggest that the shift-level production estimates might be more reliable over the long run. However, these estimates are only valid in conditions similar to those observed on the Hungry Bob timber sale. The production model taken form the detailed time study data is much more flexible in terms of diameter, species composition, distance between trees, and live vs. dead trees and can cover a broader range of conditions. Anyone using this model for prediction should keep this discrepancy in mind and allow for it in cost calculations. A suggestion for how to accomplish this would be to decrease the efficiency rates used to adjust for delays.

5.2.2 Forwarder

5.2.2.1 Production Models

The original intent was to use the GPS data to validate the production model that was created from the forwarder detailed data. Because only about half the stops recorded during the detailed time study could be detected in the GPS files, this was not a viable option. Therefore none of the forwarder production models have been validated.

T-tests were run to determine if there was a difference in cycle times between machines. There was no statistical difference between any of the machines in the detailed data. In the shift-level data, there was no difference found between the two Rottne forwarders, however a difference was found between each of the Rottnes and the Timbco. This is why in the following models the machine is not present in the detailed model and is designated only as Rottne/Timbco in the shift-level model.

The shift-level data produced the following model for estimating production of the basis of loads per productive machine hour:

$$\text{Load/PMH} = 1.4047 - 0.2358\ (\text{Rottne})$$

Where:

Rottne = binary indicator variable, 1 = Rottne SMV Rapid or Rottne Rapid, 0 = Timbco

This model has the following characteristics:

Table 5.21 Statistics for dependent and independent variables used in shift-level forwarder production model

Dependant Variable	Parameter	Coefficient	Standard Error	t statistic	P Value	Adjusted R^2
Loads per SMH			0.0384			0.1354
	Intercept	1.4047				
	Rottne	-0.2358	0.0754	-3.1256	0.003	

This model shows that the Rottne SMV Rapid and the Rottne Rapid on average produced 0.24 fewer loads per productive machine hour.

The model created using detailed data predicts the minutes required to make one full cycle is as follows:

$$\text{Minutes per Cycle} = 1.4675 + 0.3486\ (\text{Stops}) + 0.0083\ (\text{Distance})$$

Where:

Stops = Number of stops to load the forwarder during one full cycle

Distance = total round-trip travel distance in feet

The detailed model is valid for the cases described in Table 5.8 and Table 5.9 and has the following characteristics:

Table 5.22 Statistics for dependent and independent variables used in detailed forwarder production model

Dependant Variable	Parameter	Coefficient	Standard Error	t statistic	P Value	Adjusted R^2
Minutes per Load			1.6418			0.661
	Intercept	1.4675				
	Stops	0.3486	0.1006	3.4637	0.003	
	Distance	0.0083	0.0030	2.7856	0.013	

This model shows that as both the distance and the number of stops increase, the cycle time increases.

The model created from the GPS data predicts the minutes required to make a complete cycle and is as follows:

$$\text{Minutes per Cycle} = 22.3688 + 0.0120\,(\text{distance})$$

Where

Distance = round trip travel distance in feet

The GPS model is valid only for the conditions listed in Table 5.11 and has the following characteristics:

Table 5.23 Statistics for dependent and independent variables used in GPS forwarder production model

Dependant Variable	Parameter	Coefficient	Standard Error	t statistic	P Value	Adjusted R^2
Minutes per Cycle			1.2607			0.295
	Intercept	22.3688				
	Distance	0.0120	0.0020	6.0177	0.008	

This model shows that as distance increases, so does the cycle time.

5.2.2.2 Utilization Rates

As with the harvester data, forwarder production estimates need to be adjusted for delays, both large and small. The GPS data did not give reliable delay estimates for two reasons. First, the resolution of the data was not fine enough to catch many of the small delays, such as those shorter than 4 or 5 minutes in duration. Second, when a large delay occurred, the machine was often shut down, also shutting down the GPS unit. The utilization rates used are taken from the detailed time study data for the small delays and from the shift-level time study data for the large delays (Table 5.24) and are similar to those found for the feller-buncher.

Table 5.24 Small and large delay utilization rates for the forwarder

	Small Delay Utilization Rate (< 10 minutes)	Large Delay Utilization Rate (> 10 minutes)
Detailed Time Study	8 %	
Shift-level Time Study		14 %

5.2.2.3 Production Comparisons

Average conditions were assumed for all three forwarders and used in the production models presented in 5.2.2.1. These average conditions included an average distance of 2000 feet and 64 stops. Production estimates from the detailed time study data were adjusted for both small and large delays. Production estimates from the shift-level time study data were adjusted for large delays only. GPS production estimates were adjusted for large delays. All estimates were then converted to $/ton. These figures are presented in Table 5.25.

Table 5.25 Forwarder production comparisons

	Detailed min/turn	Detailed tons/PMH	Scheduled $/ton	Shift turns/PMH	Shift tons/PMH	Scheduled $/ton	GPS min/turn	GPS tons/PMH	Scheduled $/ton
Adjusted R^2	0.699			0.135			0.295		
S_x	1.6418			0.0377			1.2607		
Timbco	40.303	18.311	$7.12	1.405	17.281	$6.94	46.298	15.940	$7.53
Rottne SMV	40.303	18.311	$7.61	1.169	14.378	$8.92	46.298	15.940	$8.04
Rottne	40.303	18.311	$6.68	1.169	14.378	$7.82	46.298	15.940	$7.05

Applying the standard error of the mean of each model to the production estimates, an idea of the relative accuracy of each model can be gained. This information is presented in Table 5.26 and Figure 5.10 for the estimates derived from the detailed data, Table 5.27 and Figure 5.11 for the estimates derived from the shift-level data, and Table 5.28 and Figure 5.12 for the estimates derived from the GPS data.

Table 5.26 Relative confidence of forwarder detailed production estimates at 95% confidence

	Timbco	Rottne SMV Rapid	Rottne Rapid
Lower Limit	$6.83	$7.30	$6.40
Average	$7.12	$7.61	$7.58
Upper Limit	$7.41	$7.92	$6.95

Table 5.27 Relative confidence of forwarder shift-level production estimates at 95% confidence

	Timbco	Rottne SMV Rapid	Rottne Rapid
Lower Limit	$6.76	$7.82	$7.58
Average	$6.94	$8.04	$7.82
Upper Limit	$7.73	$8.26	$7.25

Table 5.28 Relative confidence of forwarder GPS production estimates at 95% confidence

	Timbco	Rottne SMV Rapid	Rottne Rapid
Lower Limit	$7.32	$7.82	$6.86
Average	$7.53	$8.04	$7.05
Upper Limit	$7.73	$8.26	$7.25

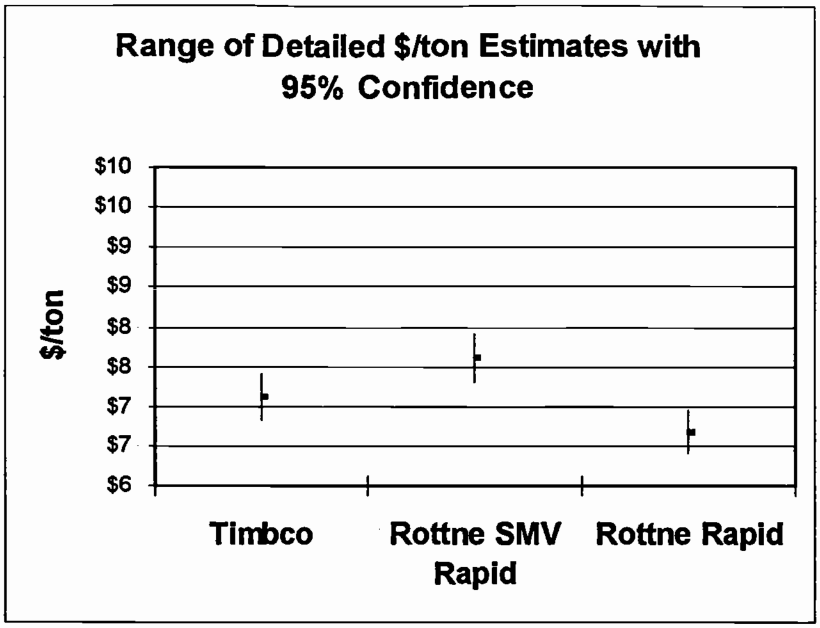

Figure 5.10 Relative confidence of detailed forwarder production estimates at 95% confidence

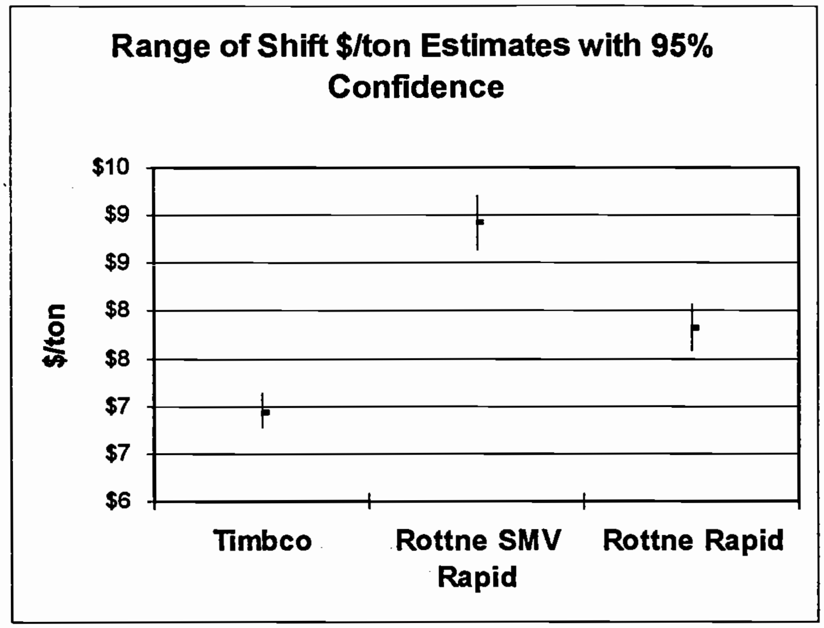

Figure 5.11 Relative confidence of shift-level production estimates at 95% confidence

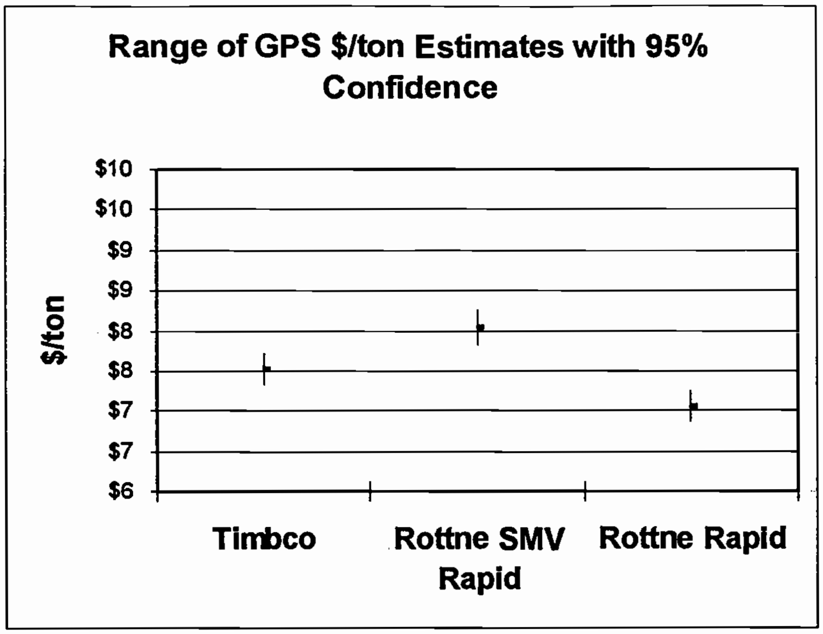

Figure 5.12 Relative confidence of GPS production estimates at 95% confidence

The range of estimates from the detailed models is $0.68/ton for all three forwarders. For the shift-level models the range of estimates are $0.36/ton for the Timbco and $0.52/ton for both Rottne machines. The range of estimates from the GPS production models is $0.48/ton for each of the three machines. As can be seen in Figure 5.13, there is no statistical difference in the estimates from the shift-level and the GPS models. The estimates gained from the detailed model are statistically different that either of the other two models. T-tests were run to confirm this.

Figure 5.13 gives a comparison of the three forwarder production estimates. It is difficult to determine if one model is better than the others in the case of the forwarder. The shift-level estimate is able to discern between the Timbco and the Rottne but the others are not, it is produced from the largest sample size of the three, 892 loads, but it also has the lowest adjusted R^2 at 0.135 and is the least flexible model. The GPS model

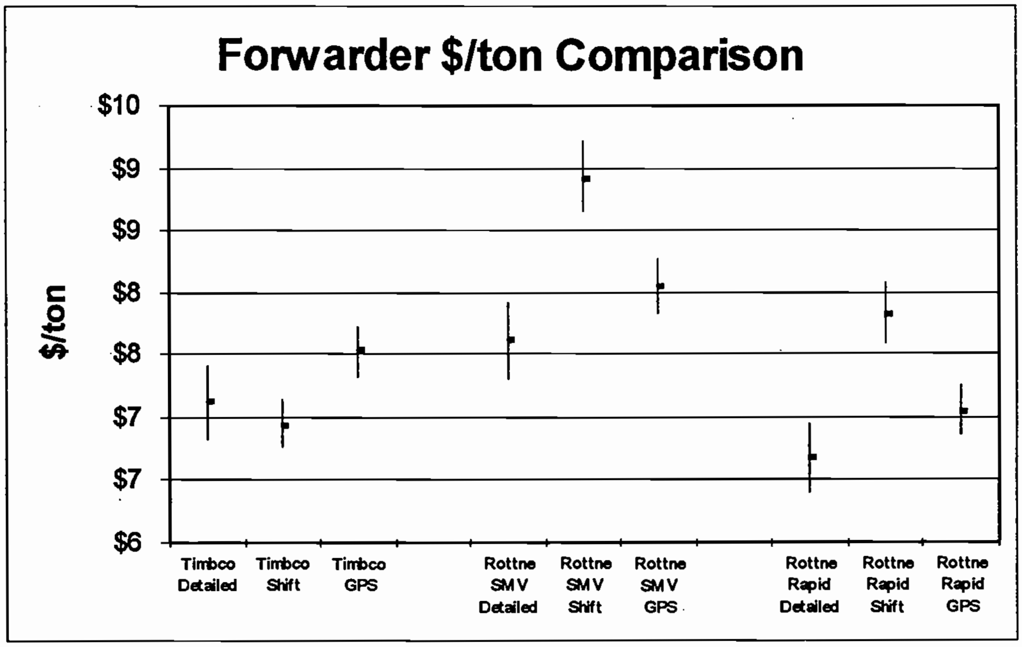

Figure 5.13 Comparison of forwarder estimates of $/ton

has a higher adjusted R^2 at 0.295, is taken from a sample of 85, can be used to predict cycle times with differing travel distances, but also only covers two of the 9 units harvested on Hungry Bob. The detailed production model has the highest adjusted R^2 at 0.661 but comes from the smallest sample size, 19. The detailed production model can be used to predict cycle times for the broadest range of conditions and gives a production estimate intermediate to the two other models.

5.2.3 The System as a Whole

To take a look at the entire system production rates from sections 5.2.1.3 and 5.2.2.3 can be added together to get a view of the production of the system as a whole. Table 5.29 gives production rates and cost for the six machines involved in the Hungry Bob study. All production rates and costs are taken from detailed production models.

Table 5.29 Production rates and costs from detailed production models

	tons/SMH	$/ton
Feller-Buncher		
Rottne SMV Rapid EGS	26.230	$5.20
John Deere 653E	18.666	$6.63
Cat 320L Excavator	15.862	$7.97
Forwarder		
Timbco 815	12.913	$7.12
Rottne SMV Rapid	12.913	$7.61
Rottne Rapid	12.913	$6.68

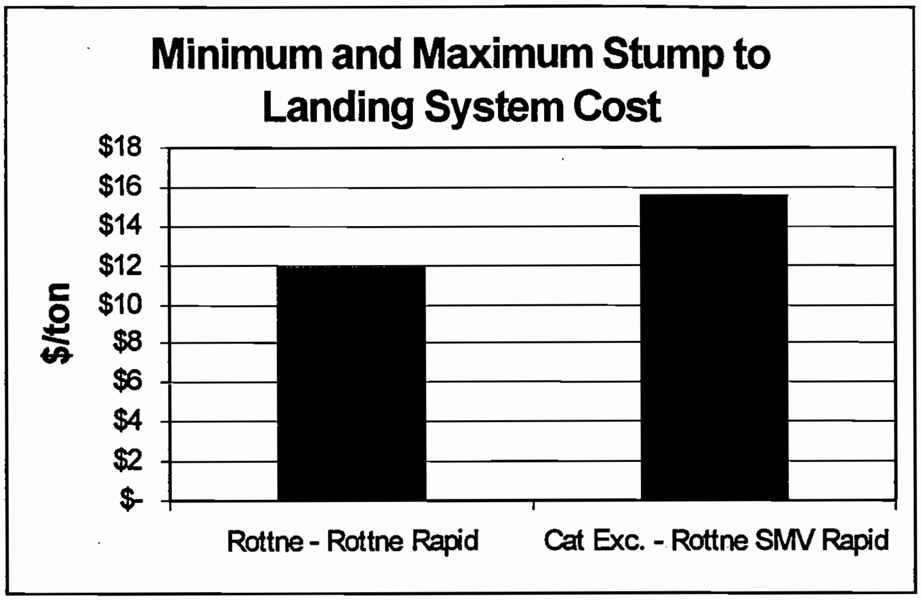

Figure 5.14 Minimum and maximum system cost

Figure 5.14 gives minimum and maximum stump to landing costs as estimated by detailed production models. Using these estimates over average conditions found on Hungry Bob, a low cost of $12.27/ton can be expected for the Rottne feller-buncher and Rottne Rapid forwarder and a high cost of $15.81/ton for the Cat Excavator feller-buncher and the Rottne SMV Rapid forwarder. The logging contractor on the Hungry Bob Timber Sale was receiving $30/ton stump to landing. Keep in mind the above production cost estimates do not include overhead such as crew pickups and equipment shop or management costs.

6.0 Discussion

6.1 Sensitivity Analysis

A sensitivity analysis was preformed for each component of the detailed production models for both the feller-buncher and the forwarder. For each of these analyses, all values were held constant at average values except for the one variable under consideration.

6.1.1 Feller-Buncher

The first variable analyzed for sensitivity in the feller-buncher production model was diameter. Figure 6.1 shows the results of this analysis.

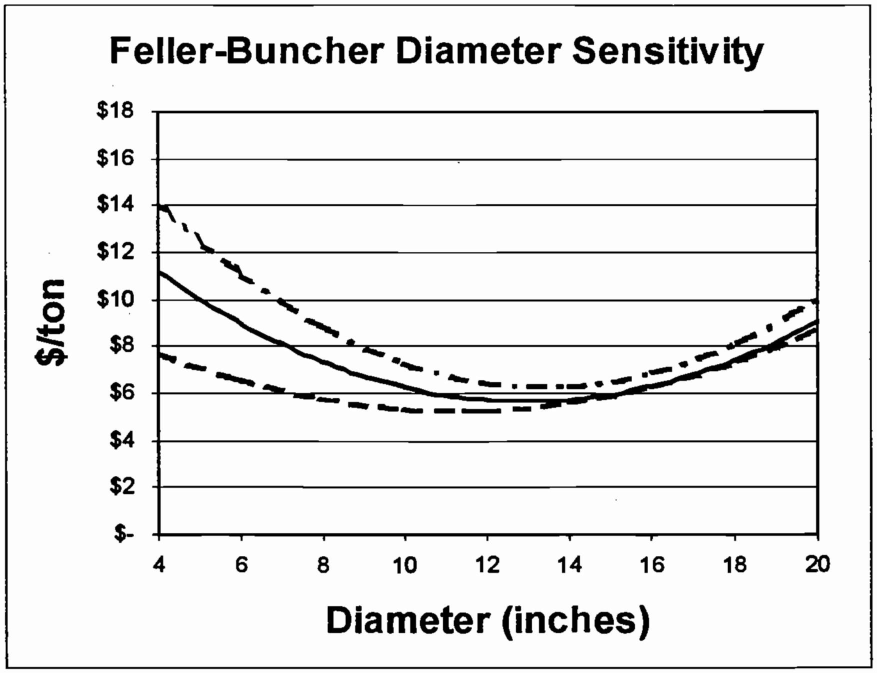

Figure 6.1 Feller-Buncher sensitivity to diameter

At smaller diameters, each tree takes less time to cut, but less merchantable weight is gained from each stem. This analysis could be greatly improved with better tree/log weight figures. The ton/tree for each diameter class was estimated by calculating the number of sawlogs and pulp pieces that could be produced for each. Average sawlog and pulp weights were then applied. It is intuitive that 16 foot sawlogs from larger diameter trees would weigh more than 16 foot sawlogs from a smaller diameter tree. Unfortunately this data is unavailable for this study, so an average had to be used. With more correct log weights the $/ton at the larger diameters would be even more favorable.

The next sensitivity analysis done for the feller-buncher was the effect of travel distance between trees. This analysis is presented in Figure 6.2.

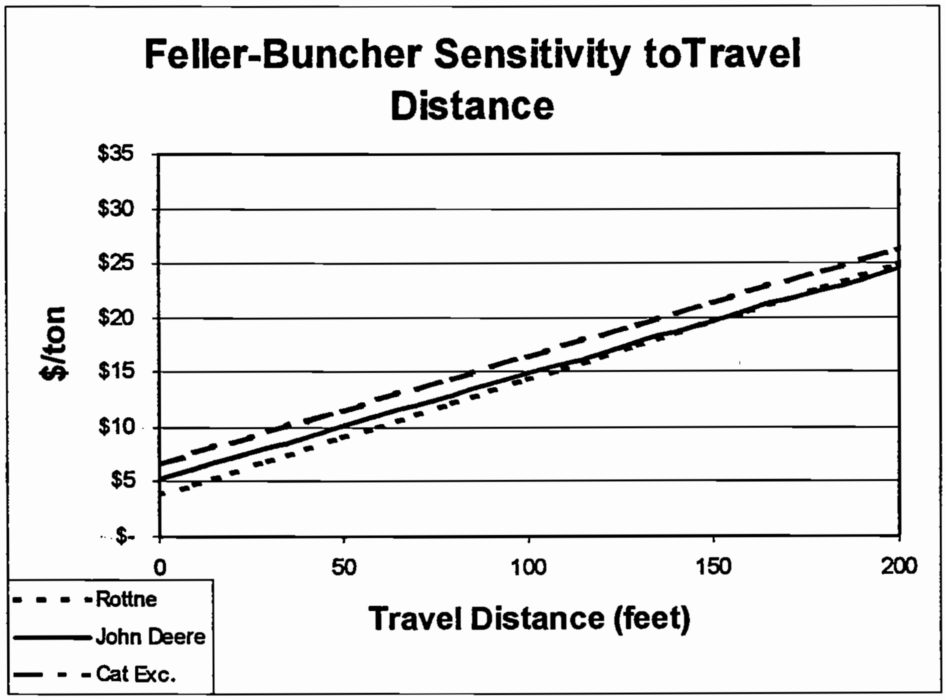

Figure 6.2 Feller-buncher sensitivity to travel distance

As can be seen in Figure 6.2 the production cost raises approximately $1/ton for every 10 foot increase in travel distance between trees. The $/ton estimates for the Rottne and John Deere cross at 162 feet. This is an extreme case and would probably not be the average on most timber sales.

Another variable looked at was species composition. The detailed model dealt with ponderosa pine and Douglas-fir only. Figure 6.3 shows the production cost tradeoff between these two species.

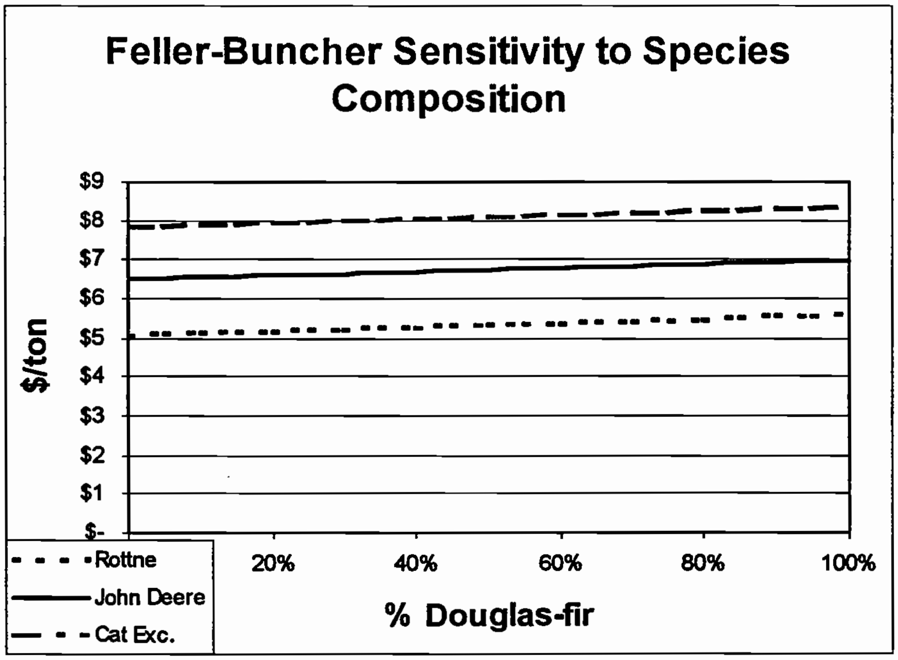

Figure 6.3 Feller-buncher sensitivity to species composition

Figure 6.3 shows that there is very little fluctuation in cost from a pure ponderosa pine stand (0% Douglas-fir) to a pure Douglas-fir stand (100% Douglas-fir). The cost difference is \$0.53/ton for the Rottne, \$0.48/ton for the John Deere, and \$0.49/ton for the Cat Exc..

The next variable analyzed for sensitivity was the percent of standing dead material present. The results of this analysis are presented in Figure 6.4.

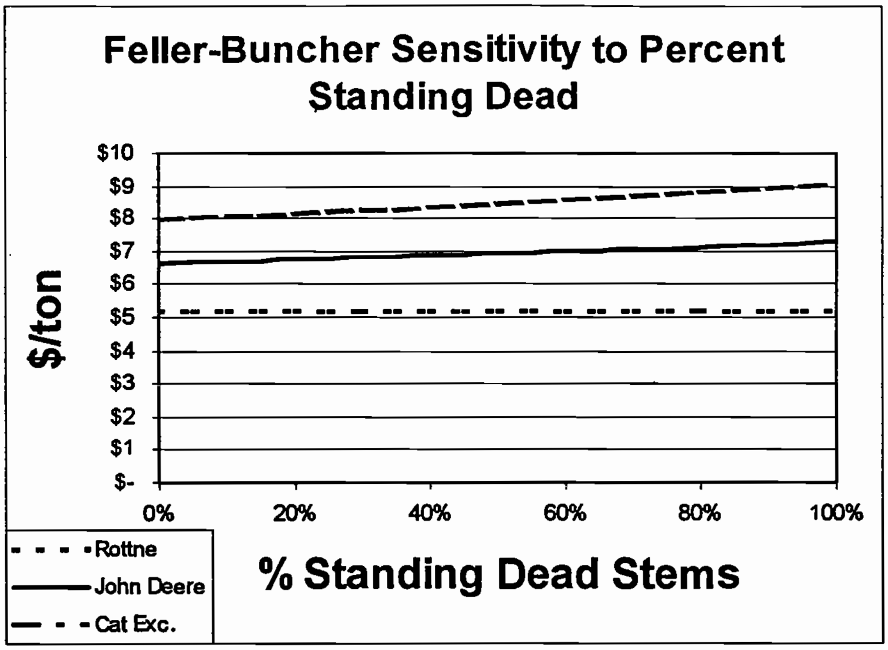

Figure 6.4 Feller-buncher sensitivity to percent standing dead

Standing dead stems were assumed to produce 2 pulp logs as opposed to the one sawlog and one pulp log produced by a standing live stem. This was reflected in the weight per piece, 0.227408 tons/stem for the standing dead versus 0.306958 tons/stem for the standing green. Keep in mind the value of the harvested material will go down as the percent pulp goes up, lowering the breakeven point, which is not reflected in Figure 6.4. The Rottne is able to keep production costs approximately equal across the spectrum of percent standing dead while the John Deere and Cat Exc. experience an increase in cost per ton.

Along the same lines as Figure 6.4 is the next analysis looking at the feller-buncher sensitivity to percent down dead stems. The results of this analysis are presented in Figure 6.5.

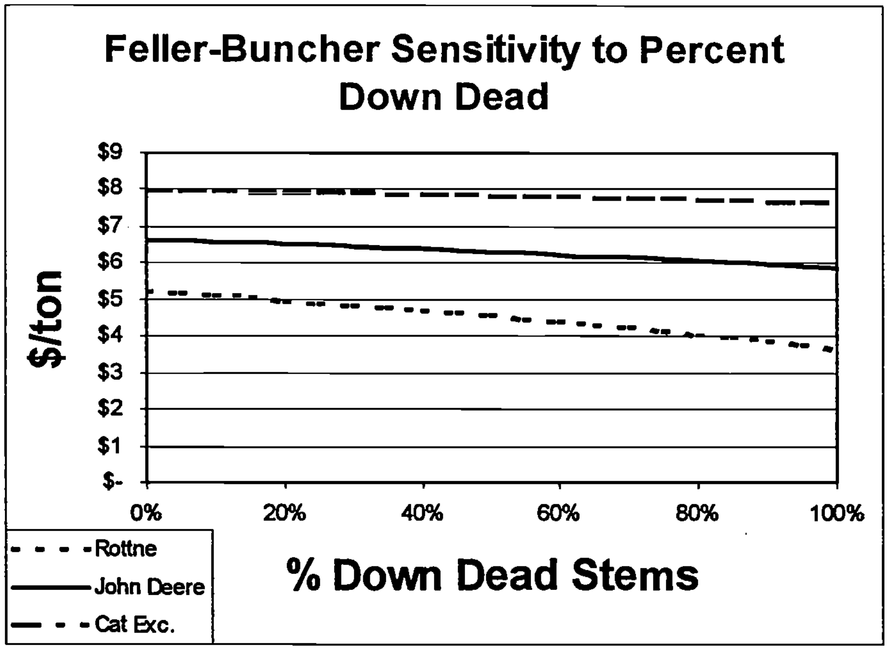

Figure 6.5 Feller-buncher sensitivity to percent down dead stems

The same volume assumptions used in the previous analysis are also used here. Keep in mind that as the percent down dead stems increases, the value of the wood removed will go down, reducing the breakeven point of the operation. Here the Rottne experiences the largest drop in production cost from a pure standing green stand (0% down dead stems) to a pure stand of down dead material (100% down dead stems), $1.57/ton. The John Deere is able to decrease its production cost by $0.75/ton and the Cat Exc. $0.35/ton. Depending on the drop in value of the wood removed, the breakeven point for each machine could be determined.

6.1.2 Forwarder

The next analysis holds the distance constant at 2000 feet and looks instead at the production cost sensitivity to the number of stops required to make a load. The number of stops will increase with increased cut tree spacing. This increase in number of stops will most likely be accompanied by an increase in travel distance. The results of this analysis are presented in Figure 6.6.

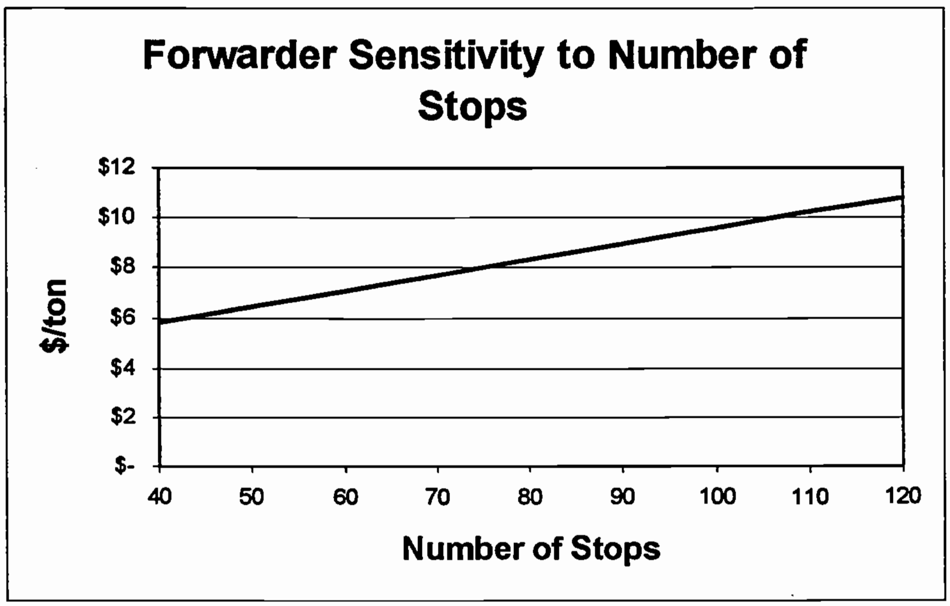

Figure 6.6 Forwarder sensitivity to number of stops

Figure 6.6 shows an increase of approximately $0.06/tons per additional stop made by the forwarder. The number of stops presented is within the range of number of stops observed during the detailed time study.

6.2 Suggestions for Future Studies

6.2.1 Detailed Time Studies

6.2.1.1 Feller-Buncher

Volume calculations and comparisons to shift-level production estimates would have been easier if the number of sawlogs and pulp pieces had been recorded for each stem cut. This would have also facilitated an answer to a commonly asked question of weather it takes any longer to cut and process a sawlog as compared to a pulp piece. Of even more use would have been to record the small end diameter for each piece. However, with each stem averaging half a minute to travel to, cut, and process into log lengths, this request may be too much for the researcher to try and keep track of in such a short time period.

6.2.1.2 Forwarder

Sample sizes for the forwarder were much too small although roughly the same percentage of turns was observed as compared to the harvester. This comes down to spending more time conducting detailed time studies on the forwarder in order to get a statistically larger sample.

Another improvement on the forwarder detailed time study would be to record distances in the field. The GPS data was not consistent enough to depend on for distances. Distances would most easily be recorded by noting the distance moved between each stop.

6.2.2 Shift-Level Time Studies

It would have been easier to analyze shift-level data if all harvesters had been capable of giving the same production measurers at the end of the day. However, this is a function of the individual harvester and is nothing a researcher can control.

6.2.3 GPS Tracking of Forest Machinery

Researchers should expect instrumentation of any kind, including GPS equipment, to be damaged during harvesting operations and prepare accordingly. GPS antennas are expensive and may be the exception to this, but cords, batteries, and other commonly replaced components of the GPS system should be available and on hand. If a spare antenna cord had been on hand the recording of GPS data could have continued on at least one forwarder for a longer duration and in more harvest units. This would have added significantly to the weight of the GPS data.

The placement of the GPS antenna on the forwarders had a significant impact on the quality of data. On the Rottne, the antenna was on top of the cab with no parts of the machine obstructing satellite signals. Additionally, the loading boom on the Rottne was positioned in front of the cab, not over the cab as with the Timbco and so was not disrupting satellite signals. The Rottne had a guardrail along the edge of the top of the cab, protecting the antenna from branches brushing by. The placement of the antenna on the Timco was initially on top of a ledge directly behind the cab. Approximately one-third of the sky was obstructed. The boom continuously moving and interrupting many of the satellite signals compounded this problem. On the first turn of the day the antenna was moved to the top of the cab it was caught by a branch and run over by the Timbco, through no fault of the operator. There was no guardrail on the top of the Timbco to prevent the antenna from being swept off the cab.

GPS provides a useful intermediate between detailed and shift-level time studies. It would be especially useful when determining soil impacts and skid trail locations. Not only is a detailed map made of where each machine went, it also provides the number of passes made on each portion of each trail recorded. GPS provides a means for researchers to locate exactly where skid trails were on the ground using the detailed location information provided at each point taken by the GPS. This is a technology that is becoming more prominent in the forest industry, with new developments and uses constantly being discovered.

6.2.4 Volume Data

All volume data used consisted of average weights for sawlogs and pulp pieces regardless of size. There are a couple of possible ways this could be improved. First, if localized volume/weight figures were developed, logs could be scaled, preferable in ft^3 or m^3, then converted to a weight. This could help adjust volumes for diameter.

A second option would be to actually weigh a sample of logs, both sawlogs and pulp logs, in the field. This would be difficult to do, as many of the sawlogs could not be easily lifted by hand. Another approach in this same direction would be to weigh the forwarder at the landing with and without a load. If the number of sawlogs and pulp pieces is known, a better idea of average piece weights could be determined. Again, this is relatively impractical to carry out. The movement of a scale this large would be difficult. Forwarders changed landings often. Landings were along the sides of roads and when they got large, could become quite long. This meant that forwarders often had to move quite a distance to unload each load.

From mill scale reports, a good estimate of sawlog weights could be obtained. There was no information of this type for the pulp logs. This information could have been obtained by counting the number of pieces on a pulp load and recording the ticket number to later match up with the load weight. Hundreds of pulp pieces were required to make one full truckload. This meant that counting individual sticks in a load would be a timely process, and one which many of the truck drivers would not have wanted to do.

7.0 Conclusion

Going back to the hypotheses discussed in 3.1, the following was determined:

1. The three feller-bunchers had different production and cost rates, therefore the alternative hypothesis was accepted.
2. Using shift-level time study data, a difference could be detected between the Timbco and the two Rottne forwarders, but not between the two Rottne forwarders, therefore the alternative hypothesis was accepted.
3. There was a difference between the production and cost estimates received from GPS, detailed, and shift-level models, therefore the alternative hypothesis was accepted.
4. Feller-buncher production and unit cost could be explained by distance traveled, diameter, species, and position, therefore the null hypothesis was not rejected.
5. Forwarder production and unit cost could only be explained by distance traveled and number of stops made, therefore the alternative hypothesis was accepted.

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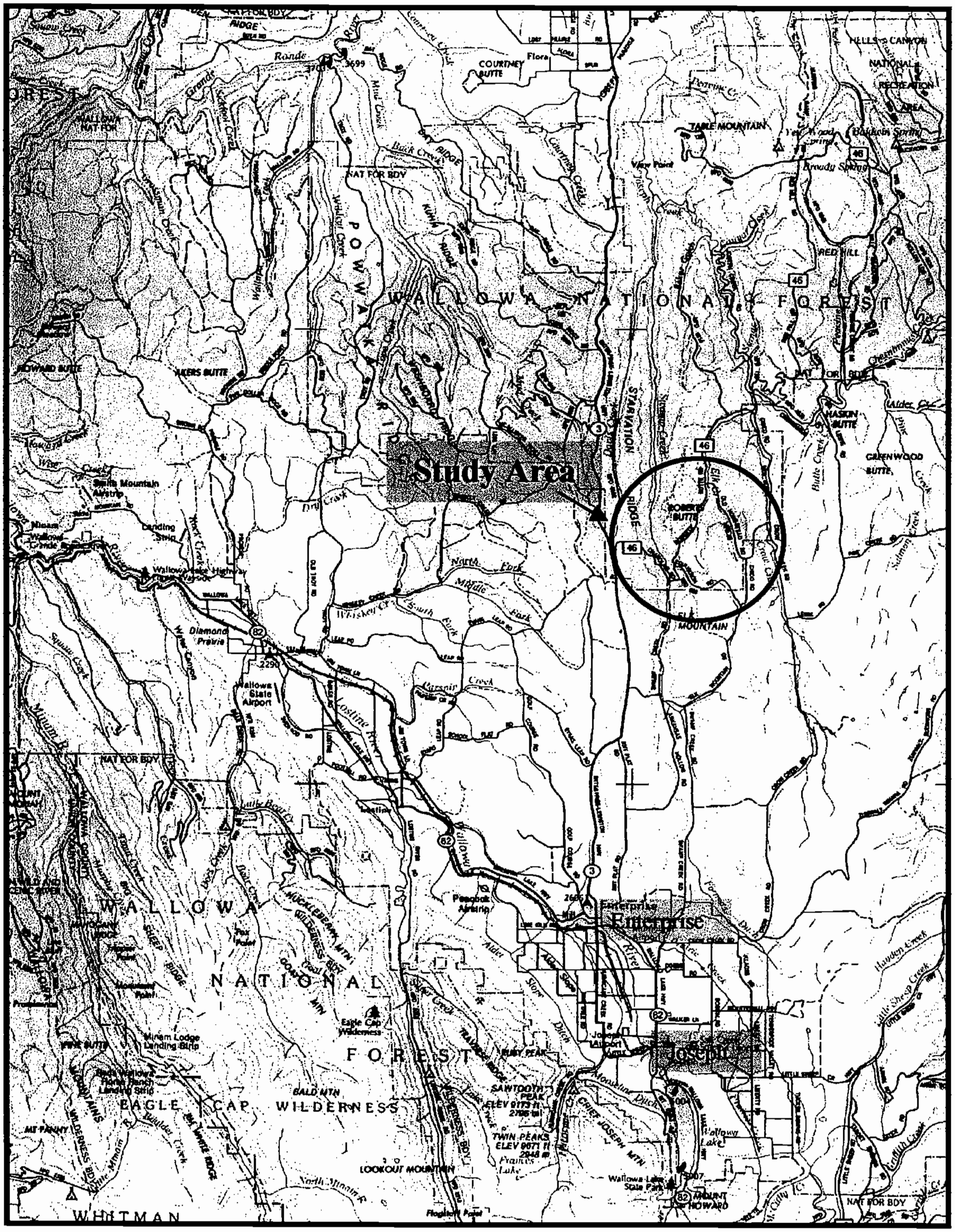
Appendices

Appendix A: Study area map



Appendix B: Shift reports

Harvester Shift Report

Operator____________________________ Unit__________________________

Start Date___________________________ Start Time______________________

End Time____________________________

Piece Counts

Total Pieces__________________________

Pulp Pieces___________________________ Sawlog Pieces___________________

Total Trees___________________________

Pulp Trees____________________________ Sawlog Trees____________________

Is this a reasonable count? (Yes) (No)

Delays longer than 10 minutes

Length	Type	Description
__________	Maintenance Mechanical Personal Other	____________________
__________	Maintenance Mechanical Personal Other	____________________
__________	Maintenance Mechanical Personal Other	____________________
__________	Maintenance Mechanical Personal Other	____________________

Where: Maintenance – regular maintenance; Mechanical – breakdown; Personal – operator-related.

Comments:____

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Forwarder Shift Report

Operator____________________ Unit____________________

Start Date____________________ Start Time____________________

End Time____________________ # of Loads____________________

Delays longer than 10 minutes

Length	Type	Description
____________	Maintenance Mechanical Personal Other	____________________
____________	Maintenance Mechanical Personal Other	____________________
____________	Maintenance Mechanical Personal Other	____________________
____________	Maintenance Mechanical Personal Other	____________________

Where: Maintenance – regular maintenance; Mechanical – breakdown; Personal – operator-related.

Load	**% Green**	**Sorted in woods**	**Sorted at landing**	**Mix**
1	0 – 20 – 40 – 60 – 80 – 100	[ ]	[ ]	[ ]
2	0 – 20 – 40 – 60 – 80 – 100	[ ]	[ ]	[ ]
3	0 – 20 – 40 – 60 – 80 – 100	[ ]	[ ]	[ ]
4	0 – 20 – 40 – 60 – 80 – 100	[ ]	[ ]	[ ]
5	0 – 20 – 40 – 60 – 80 – 100	[ ]	[ ]	[ ]
6	0 – 20 – 40 – 60 – 80 – 100	[ ]	[ ]	[ ]
7	0 – 20 – 40 – 60 – 80 – 100	[ ]	[ ]	[ ]
8	0 – 20 – 40 – 60 – 80 – 100	[ ]	[ ]	[ ]
9	0 – 20 – 40 – 60 – 80 – 100	[ ]	[ ]	[ ]
10	0 – 20 – 40 – 60 – 80 – 100	[ ]	[ ]	[ ]
11	0 – 20 – 40 – 60 – 80 – 100	[ ]	[ ]	[ ]
12	0 – 20 – 40 – 60 – 80 – 100	[ ]	[ ]	[ ]
13	0 – 20 – 40 – 60 – 80 – 100	[ ]	[ ]	[ ]
14	0 – 20 – 40 – 60 – 80 – 100	[ ]	[ ]	[ ]
15	0 – 20 – 40 – 60 – 80 – 100	[ ]	[ ]	[ ]
16	0 – 20 – 40 – 60 – 80 – 100	[ ]	[ ]	[ ]
17	0 – 20 – 40 – 60 – 80 – 100	[ ]	[ ]	[ ]
18	0 – 20 – 40 – 60 – 80 – 100	[ ]	[ ]	[ ]
19	0 – 20 – 40 – 60 – 80 – 100	[ ]	[ ]	[ ]
20	0 – 20 – 40 – 60 – 80 – 100	[ ]	[ ]	[ ]

Comments____

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