AN ABSTRACT OF THE DISSERTATION OF

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In the Blue Mountains of northeastern Oregon, prescribed fire and mechanical harvesting economics were investigated for fuels reduction and forest restoration. Using a cut-to-length harvesting system, three single-grip harvesters and three forwarders produced significantly different production rates. For the harvesters, significant variables that affected production rates were found to be: harvested material removed (live tree, standing dead tree, or downed wood), tree species, tree diameter, and distance traveled between processing. For the forwarder, significant variables that affected production rates were forwarding distance and the number of stops required to accumulate its rated payload. From the thinning, net revenues per acre ranged from $143 to $718 and averaged $315.

Prescribed fire costs ranged from $24 to $87 per acre and averaged $51. Prescribed fire intensity was found to be significantly higher in the mechanically thinned stands with tons of downed woody material being a significant predictor of

fire intensity. Mean fire intensity was found to be 94.7° and 157.6° Celsius for the burn and thin and burn treatments, respectively. The addition of activity fuel from the mechanical thinning was the primary factor that increased fire intensity.

From the production data, net revenue was determined for stump-to-mill operations and predictive equations were used to develop a cost model that investigated stand conditions of significance. This information provided a framework for conducting sensitivity analysis on the effects of these significant variables to production and cost at differing levels. Equations were derived from the simulations and used to determine alternative scenarios for stand conditions in and around the study area.

The economics of fuels reduction and forest restoration needs to proceed with an increased level of cost analysis. While many areas in need of fuels reduction have produced positive net revenues, others have produced a loss. Land mangers need to understand how equipment selection, material removed, stand conditions, market prices, and market locations affect harvesting costs and net revenue. Information provided in this paper can be used by land managers to aid in assessing the economic feasibility of a given operation and determine which treatment combinations are optimal.

Thinning with Prescribed Fire and Timber Harvesting Mechanization for Fuels Reduction and Forest Restoration.

by

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APPROVED:

Major Professor, representing Forest Engineering

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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.

Peter J. Matzka, Author

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We enter life without knowledge, a direction, a focus, a goal... As people touch our lives it changes us without them, often times, ever being aware. They impart something about themselves to us and we use that gift to make change for ourselves. Whether it be wisdom, encouragement, strength, or love; all have a profound influence. To all that have influenced me and made this adventure possible I thank you.

TABLE OF CONTENTS

TABLE OF CONTENTS (CONTINUED)

TABLE OF CONTENTS (CONTINUED)

Page

TABLE OF CONTENTS (CONTINUED)

LIST OF FIGURES

LIST OF FIGURES (CONTINUED)

LIST OF FIGURES (CONTINUED)

LIST OF FIGURES (CONTINUED)

LIST OF FIGURES (CONTINUED)

LIST OF TABLES

LIST OF TABLES (CONTINUED)

LIST OF TABLES (CONTINUED)

LIST OF TABLES (CONTINUED)

LIST OF APPENDIX FIGURES

LIST OF APPENDIX FIGURES (CONTINUED)

Thinning with Prescribed Fire and Timber Harvesting Mechanization for Fuels Reduction and Forest Restoration

Introduction

In the Blue Mountains of eastern Oregon, the dry conifer forests and much of the inland west are at risk to catastrophic wildfire. Over 80 years of fire suppression and the selective harvest of ponderosa pine (*Pinus ponderosa*) have resulted in levels of fuels that have set the stage for wildfires (McIver et al. 1997).

Fire has been an important disturbance process for millennia in the wildlands of the Blue Mountains. Records from early explorers and on many older trees suggest that fire burned at frequent intervals (fire return intervals of 5-10 years on some sites) in many of the Blue Mountain forests and grasslands (Agee 1996). Since about 1900, the forest structure and composition have changed. Most of the change is directly related to fire exclusion (McIver et al. 1997). In addition, the practice of selectively logging ponderosa pine left stands with increased densities of lodgepole pine (*Pinus contorta*) and favored Douglas-fir (*Pseudotsuga menziessi*) and grand fir (*Abies grandis*). As a result, the dense stands of these species increased the incidence of pine beetles and defoliating moths (Barret 1983). Conifer tree pathogens and climatic events, such as the severe drought conditions in the late 1980's and early 1990's, are also contributing factors (Mutch et al. 1993).

High stocking levels, reduced tree vigor, insect attack, and disease have left many of these stands with high fuel levels and wildfire potentials. With a combination of standing dead and downed trees, high levels of litter fall, and suppressed regeneration, the stage has been set for catastrophic wildfires. Several common silvicultural objectives have been noted for restoring structure and function to these forests. The first is to reduce the oftentimes high level of accumulated downed woody fuel associated with the drier forest types (Mutch et al. 1993). The second is to reduce the typically high number of non-merchantable saplings and seedlings, along with the suppressed trees which can be used as a commercial product to offset operational costs (Habeck 1994). The third is to encourage the regeneration of the native herbaceous and shrub layer, as their function is an important component for fire resistance and returning fire to the forest (Wright 1978). Finally, Habeck (1994) noted that both overstory reduction (through density management) and forest floor treatment needs to occur for successful reestablishment. Therefore, the fourth objective is to remove either with fire or through scarification, a portion of the forest floor horizon (litter and duff) and to leave some exposed mineral soil for acceptable natural regeneration (Harrington and Kelsey 1979).

While these objectives are suggestions and simple in concept, many challenges are presented to forest managers when fuel reduction activities and related management decisions need to be made in these fire-prone or altered stands. Management activities, such as fuels reduction, timber harvesting (primarily thinning from below), and prescribed fire, are encountering economic and environmental challenges. The timber products derived from the harvesting activities are the main economical benefits that are immediately recognized and offset operational costs. Due to the development and present condition of these stands, timber harvested is often small diameter with a low market value. The typically, large proportion of low value pulpwood removed with respect to the higher valued sawlogs creates the classic break-even analysis with the fluctuation of current market prices and operating costs driving the economic feasibility of an operation. In contrast, with prescribed fire comes the challenges of no revenue received, weather limitations on burn window, and smoke management.

Currently, however, considerable activity is being dedicated to improving the economics for value-added use of small diameter material through alternate products and markets rather than the traditional uses as pulpwood and dimensional lumber (LeVan-Green and Livingston 2003). Value-added uses include flooring, paneling, cabinets, furniture, and millwork with alternative market uses including biomass energy, ethanol production, firewood, and compost. While these markets will potentially develop and expand over time, the economics for harvesting small diameter material is a critical component to understanding the overall economic benefit of these different alterative.

This study examines the stand conditions or resource characteristics that have a significant influence on the production rates and associated costs of different cut-to-length harvesting equipment (single-grip-harvester and forwarder) and prescribed fire. In addition, while determining the cost and production of these systems was a main objective, another objective and important area of understanding was the affect of mechanical thinning on the prescribed fire treatment, addressing both cost and fire line intensity. Finally, knowledge of how a management decision or decisions can affect the financial outcome or feasibility of an operation is essential to understand. Managers have a need and responsibility to understand the cause and effect of a relationship with respect to decisions made and the economic outcomes, especially when it comes to the public lands.

Resource managers need better information on the comparative effects of alternative practices such as prescribed fire and mechanical "fire surrogates." An integrated national network of 13 long-term research sites (one being the Hungry Bob study area) has been established to address this need, with support from the U.S. Joint Fire Science Program and the National Fire Plan (Weatherspoon 2000). Four alternative treatments (similar to this study) will be applied in replication at each site: (1) cuttings and mechanical fuel treatments alone; (2) prescribed fire alone; (3) a combination of cuttings, mechanical fuel treatments, and prescribed fire; and (4) untreated controls. Response to treatment will be determined through the repeated measurement of a comprehensive set of core variables at each site, including aspects of fire behavior and fuels, vegetation, wildlife, entomology, pathology, soils, and economics. The experiment is designed to facilitate inter-disciplinary analysis at the site level, and meta-analysis for each discipline at the national level. The inter-disciplinary nature of the study will provide managers with information on how their practices affect whole ecosystems, while meta-analysis will provide insight on which responses are general, and which are dependent on specific environmental conditions (McIver and Matzka 2002).

The economics and operational portion of this interdisciplinary study, on the effects of fuels reduction in forest restoration and to reduce the risk of catastrophic wildfire, is an essential part that will help to provide financial insight for the implementation of these treatments. This study provides quantitative and qualitative results as to the factors affecting the economics of fuels reduction and forest restoration in the dry forests of the Blue Mountains located in Northeastern Oregon.

The relevancy and need for this information was recently identified in a summary report that outlined the current state of the knowledge on modifying wildfire behavior and the associated effectiveness of mechanically thinning, burning, or mechanically thinning and burning forest fuels (Carey and Schumann 2003). This assessment focused on the ponderosa pine forest types that had a pre-settlement history of low intensity fires in the western United States. In the report's findings, comprehensive information is limited on the effectiveness and feasibility of mechanical thinning to reduce the risk of wildfire through fuels reduction. Information is even more limited in relation to combinations of thinning and burning. They found substantial evidence that the prescribed fire treatment was effective for reducing fuels. However, they also noted regardless of treatment structure, many stands in the dry ponderosa pine forest type will require pre-treatment of forest fuels prior to an application of prescribed fire. This requirement for pre-treatment of fuels increases the need for a more comprehensive understanding of the variables that affect mechanized production and cost.

Study Objectives

The main study objectives were to determine the economic costs of mechanical thinning and prescribed fire, and to, develop a model that investigates the variables that affect treatment costs and associated benefits at the unit and landscape level in the Blue Mountains of Oregon. This was accomplished by several sub-objectives, and these sub-objectives were:

1. Determine operational production rates and economics for mechanical thinning and prescribed fire.
2. Determine the value of timber products removed during mechanized thinning.
3. Assess the degree in which pre-treatment of fuels (through thinning with a cut-to-length system) affects prescribed fire intensity response.
4. Identify how different stand conditions (e.g. live-to-dead tree ratio) and fuel loading affects the economics of operations and the value of timber removed.
5. Develop a decision matrix that identifies economic tradeoffs that occur among treatments on a unit level and across the landscape.

Literature Review

Recently, in an effort to gain an understanding into the production rates and economics associated with mechanical thinning to improve stand health and reduce wildfire risk, several studies have been completed in the Blue Mountain region of northeast Oregon. A pilot study (Deerhorn project) investigated the use of a standing skyline and single-grip harvester (SGH) to reduce stocking levels and remove standing dead and downed trees (Brown 1995, Kellogg and Brown 1995). A second study (Limber Jim project) compared the use of a SGH and standing skyline to a SGH and forwarder in a cut-to-length (CTL) operation (Drew et al. 1998, McIver 1998, Doyal 1997). Both studies focused on the reduction of fuels by mechanical methods and the utilization rates of the standing dead and downed wood versus sawlogs. However, the objectives were expanded in the Limber Jim project to include environmental effects of the harvesting treatments. Both of these studies are discussed below in detail with a review of other related studies in which the CTL system was investigated.

Deerhorn Project (From Brown 1995)

The Deerhorn project, conducted in the summer of 1994, was a pilot project designed to answer the following questions:

1. Can fuel loads be acceptably reduced with a SGH (single-grip-harvester) combined with a small skyline yarder?
2. Is it economically feasible to harvest fiber material and small sawlogs with such a system?
3. What degree of soil disturbance and compaction can be expected with a harvester/yarder combination?
4. What effect does the system have on small mammal and log-dwelling ant populations?

The study site consisted of a 50-acre harvest unit located southwest of Pendleton, Oregon. The terrain was relatively flat with slopes under 10%. Stand structure was variable with an average diameter at breast height (DBH) of 9 inches, and in some areas as many as 1000 stems per acre. In the 1970's, the mountain pine beetle (*Dendroctonus ponderosae*) attacked the stand, which left most of the lodgepole pine dead and eventually on the forest floor. The silvicultural prescription included the following points: reduce the fuel loading, increase stand vigor by eliminating diseased trees and thin the green trees to 80-90 trees per acre (tpa), retain 50 pieces of woody debris per acre, and provide some late forest structure in a landscape dominated by pine.

The harvesting equipment included a Koller K501 yarder (trailer mounted) combined with an Eagle Eaglet carriage. The carriage was a radio-controlled slack-pulling carriage on a standing skyline, slackline system with intermediate supports and tailtrees. With a 4-person crew, the owning and operating cost of the yarder was calculated to be $132.79/SMH (scheduled machine hour). The SGH was a Link Belt 'C' Series II tracked carrier (LS 2800), a Pierce modified harvester boom, and a Waratah 20-inch single-grip hydraulic tree felling and processing head. Hourly owning and operating cost (with operator) was calculated to be $89.41/SMH. Loading cost was $67.64/SMH using a John Deere 690 ELC grapple loader. All harvesting layout occurred prior to logging. Potential skyline corridors, tailtrees, and intermediate supports were located and flagged using a corridor centerline spacing of 150 to 250 feet. The harvester operator removed standing, unmarked trees as well as processed the downed material on the forest floor. Moving parallel to the skyline corridors, the harvester processed strips approximately 50 feet in width.

Logging productivity rates for both the harvester and yarder are summarized in Table 1. Utilization rates for the harvester and yarder were 80% and 57%, respectively. Timber removed from the site consisted of 42% live, 14% standing dead, and 44% dead and down.

The percent species composition removed from the stand determined by board foot volume, was 23% Douglas-fir, 31% grand fir, 33% lodge pole, 1% ponderosa pine, 12% western larch (*Larix occidentalis*). The gross volume removed and scaled at the mills was 29% sawlogs, 60% pulpwood, 11% cull and deduction.

Table 1 Production rates for SGH and yarder on the Deerhorn project.

	SGH		Yarder	
	Prod/ SMH	Prod/ PMH	Prod/ SMH	Prod/ PMH
Logs	151.5	188.5	78.5	139.0
Ft^3	589.4	733.3	305.4	540.7
Bdft	2918	3631	1512	2677
Tons	13.5	16.8	7.0	12.4

Total revenue was determined using the present market prices at the time of the study. Sawlogs and pulpwood generated revenue of $515/MBF and $36/ton respectively, at the mill. The calculated logging costs for the different pieces of equipment are shown in Table 2.

Table 2 Logging costs for Deerhorn project.

	$/Cunit	$/Mbf	$/ton	$/m³
Layout	1.45	2.93	0.64	0.51
Harvester	15.92	32.11	6.97	5.62
Yarder	40.53	81.78	17.74	14.31
Loader	18.15	36.61	7.94	6.41
Trucking	20.19	42.19	9.15	7.39
TOTAL	96.97	195.6	42.44	34.24

Total revenue was calculated to be $103,258, and total owning, operating, and labor cost was found to be $78,808 (with no profit or risk allowance) which produced a net profit of $24,250. Thus, the study concluded that it was economically feasible to combine a SGH and a small cable yarder on flat ground in a fuel reduction treatment (in this case study). A key factor was the component of higher value sawlogs (29% in this study).

Fuel loading prior to harvest averaged 47.8 tons per acre, with 40% of the fuel occurring in the 3-9 inch diameter classes. There was an overall 20% reduction of fuels due to the harvesting. The 3-9 inch and 9-20 inch diameter class were reduced by a total of 20%, while all other diameter classes increased. Fine fuels in the 0-3 inch diameter class were increased due to the activities of the harvester and the processing of trees into short log lengths in the stand. These fuels should decompose in a relatively short time frame following harvest. Large fuels, greater than 20 inches, were left in the stand to enhance wildlife habitat.

Limber Jim Project (From Drews et al. 1998)

The main objective of the Limber Jim study, conducted in the summer of 1996, was to compare the use of a SGH and small cable yarder with a CTL harvester/forwarder system. The overall management objectives of the fuel reduction project were to reduce crown fire potential, meet soil protection standards, and pay for the operations with harvesting revenues. The following items were measured in the study:

1. Fuel loading before and after harvest
2. Harvesting related soil disturbance and compaction impacts of harvesting on soils
3. Logging production rates, harvesting costs, and revenues

The study was located on the Wallowa-Whitman National Forest near the La Grande municipal watershed in northeast Oregon. The study design included seven distinct research units from a pool of 18 units. The research units ranged from 6.5 to 23 acres in size, and percent slopes ranged from 0% to 20%. The average DBH was 7 inches with approximately 250-300 tpa removed. Chip material removed was 54 and 42 green tons/acre for the skyline and CTL system, respectively. In addition, there were 4 and 6 green tons/acre of saw logs removed (skyline and CTL, respectively). Stands were either mixed conifer with grand fir, western larch, and Douglas-fir, or primarily lodgepole pine. The mountain pine beetle and the western spruce budworm had severely damaged the stands (similar to the conditions found in the Deerhorn project). The attacks on these stands left many standing dead and downed trees. Fuel loadings were some of the highest in the area, with up to 80 tons/acre. The silvicultural prescriptions varied somewhat from unit to unit, however, all standing dead and downed trees in the 4 to 15 inch DBH range were removed. Trees were marked either for leaving or for cutting, depending on the specified volumes of green tree removal. An overall target residual tpa was not required and left as a unit-by-unit decision.

The harvesting equipment included two SGH's. Both were 1991 Hitachi 200LC excavators fitted with 1992 Keto 500 harvesting heads. The owning and operating cost of each harvester was $114.00/SMH. The cable yarder was a 1997 Diamond D210 3-drum swing yarder (track mount) combined with an Eagle Eaglet carriage. The yarder used a standing skyline, slackline system with tail trees and intermediate supports, when needed. With a 5-person crew, the owning and operating cost of the yarder was calculated to be $230.00/SMH. The cable yarding operation also used a John Deere 690 knuckleboom loader for sorting and stacking logs ($73.00/SMH). The forwarder in the CTL system was a 1996 Valmet 646 (12-ton capacity), with an owning and operating cost of $80.00/SMH. A Morbark 27-inch disk chipper was on site for processing pulp for both systems. Limited to eight truckloads of chips per day, the owning and operating cost was $93.00/SMH. Timber removed from the study units was 19% live, 26% standing dead, 55% dead and down. The breakdown of volume harvested was 12% sawlogs and 88 % pulpwood for the skyline system and 6% sawlogs and 94% pulpwood for the CTL system.

Table 3 shows the logging productivity and costs for the different pieces of equipment in the skyline and CTL systems. The logging productivity rates that were observed from the skyline and CTL systems were 13.5 tons/SMH and 10.3 tons/SMH, respectively. Revenues from timber harvesting are shown in Table 4.

Total revenue was determined from the market price at the time of the study. Sawlogs generated $425/MBF, which converted to $86.00/green ton. Delivered value for chips was $97.50/BDU (bone dry unit), equivalent to $59.00/green ton. Subtracting the stump to mill costs, the forwarder system produced net revenues of $19.50/ton ($1112/acre), and the skyline system lost $9.50/ton ($479/acre).

Table 3 Logging productivity and costs for skyline and CTL systems on the Limber Jim project.

	Skyline		CTL	
	Tons/ SMH	$/ton	Tons/ SMH	$/ton
Layout		1.38		
Harvester	5.9	19.32	8.9	12.86
Yarder or Forwarder	10.3	29.54	13.5	5.93
Chipper	19.8	4.13	19.8	4.4
Loader		0[1]	30.0	0.15
Trucking		18.15		18.15
Stump-to-Mill		72.51		41.49

[1]Included with yarding cost

Table 4 Gross revenue per green ton and per acre.

	Skyline		CTL	
	$/ton	$/acre	$/ton	$/acre
Chips	59	2512	59	3181
Sawlogs	86	500	86	302
System Average	63	3012	61	3483

Harvester costs were higher for the skyline system than the forwarder system due to the increase in corridor spacing compared with closer spaced forwarder trails. With skyline corridors spaced approximately 120 feet between centerlines, compared to 60 feet for the forwarder, the harvester had to spend more time positioning and bunching logs for the cable yarder. Costs for the skyline system were also higher than those found in the Deerhorn project. Factors, such as a decrease in sawlog percentage, increased fuel loading, and higher equipment owning and operating costs, resulted in an increase in harvesting cost.

Fuel loading prior to harvest averaged 55.6 tons/acre. There was a 52% reduction in fuels due to harvesting. Fuel was reduced in all fuel classes except the 0-3 inch diameter class, where tonnage increased by an average of 11% due to the addition of activity fuels left by the harvester. Fuel reduction was the greatest in the 3-6 inch size class (47% of pre-treatment), followed by the 6-9 inch size class (29% of pre-treatment). Statistically, the skyline and CTL system produced similar fuel reduction patterns.

Of the seven study units, 6 had overall soil disturbance levels under 10% of the total area. Soil disturbance in this study was defined as areas where soils were either compacted or displaced. The CTL and the skyline system averaged 6% and 7%, respectively, total soil disturbance for the harvested areas. There was no statistically significant difference in soil disturbance between the two systems at the 95% significance level.

Related Studies in Thinning with Timber Mechanization

In addition to the two studies summarized above, other studies over the past decade have focused on the relatively new mechanized technology entering the woods. A compendium of mechanized harvesting research was published by Kellogg et al (1992) which summarized much of the early work. In more recent efforts, more detail is being investigated as to what affects mechanized harvesting (i.e. stand composition, species, operator experience, and terrain) with respect productivity. Further, comparisons to existing small wood systems, stand damage, and soil interaction have been a primary focus.

Of the earlier studies, many found the benefit of a CTL system with respect to efficient felling of small diameter material (Anderson 1991). Stems sizes smaller than 22" could be optimized into higher quality dimensions with a greater consistency compared to manual methods (Anderson 1991). Makkonen (1991) noted that productivity was significantly influenced by tree size with a positive correlation between production and stem size (within the range of the harvesting heads capabilities). Number of stems removed per acre, branch size, and percent slope were also significant factors that affected harvester production (Raymond and Moore 1989).

In a more recent study by Ledoux and Huyler (2001) a comparison was made between different small wood harvesting techniques (small cable yarder, CTL system, and small tractor). The study site for the CTL harvester (Huyler and LeDoux 1996) had 256 trees per acre (mostly eastern white pine and northern red oak) and a mean stand diameter of 11.2 inches. The stand prescription was primarily a thinning to reduce the basal area from 128 to 90 ft^2. The site was nearly flat except for a small area with a side slope of about 10 percent. The 55-hp CTL harvester with a Peninsuladesign roller processing sawhead (RP1600) was mounted on a modified 988 John Deere 70 tracked excavator (it had a maximum cutting diameter of 14 inches). The system included a Valmet 524 forwarder equipped with a small 8-foot log bunk. Mean hourly production (SMH) for the CTL harvester with forwarding system was 228 ft^3 (5.3 tons).

Another study conducted in 1996 by Holtzscher and Landford looked at different levels of mechanical processing. Using a Valmet 536 Woodstar harvester and forwarder the machines worked in stands with an average diameter of 9" and approximately 300 trees per acre. Production for the CTL system was reported at 7.5 tons per SMH (322.6 ft^3). A predictive equation was derived from the study for the harvesters' time to process a single tree (in 100^{th} of a minute). Reported in Holtzscher and Landford 1996 the time to process a single stem was determined to be 0.223+0.0536*(DBH), with DBH measured in inches.

A study a few years prior by Kellogg and Bettinger (1994) was conducted in a stand of Douglas-fir with a slightly higher initial tree count of 385 per acre and a higher average diameter of 13.5 inches. Production rates for the CTL system were 750 ft^3/SMH (17.4 tons).

Finally a study conducted by the California Department of Forestry looked at ways to reduce landscape, smoke emissions through alternative fuel reduction treatments in tandem with prescribed fire (CDF Smoke Management Unit 2000). In the study the team investigated the pros, cons, and costs associated with whole tree logging versus a CTL system. The intended use of the CTL system was to produce sawlogs and pulpwood for local mills and utilize other noncommercial products for firewood or landscaping material (i.e. posts) while reduction fuel loadings to allow for a potential prescribe fire. Costs to produce these products were determined to be between $25 and $35 for both pulpwood and sawlogs. The assumptions were that trees would be less than 20" DBH and slopes are less than 40%. Pros for this option over the whole tree system were:

- Equipment suited for processing very small material
- Low ground pressure
- Low potential for stand damage due to specialized equipment.
- Fuel removal and modification to an acceptable level

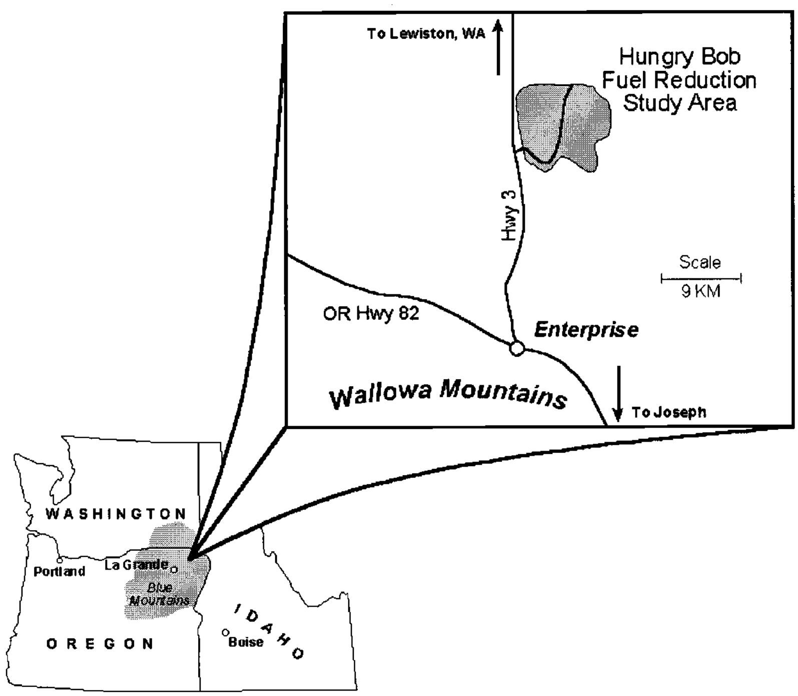
The cons were:

- Material that does not make a product stays in the forest and adds to the ground fuels (limbs and needles)
- Slow production rate
- Cost more than whole tree logging
- If not done under proper conditions follow up burn projects could damage residual trees.

Study Location and Design

The project area was located in the Wallowa Valley District (Wallowa Whitman National Forest), within the Elk Creek and Cow Creek drainage, 20 miles north of Enterprise, Oregon (Figure 1). The 30,000-acre "Wapiti Ecosystem Management Project" had a variety of stands available for study. The Wapiti management area calls for thinning and/or underburning 1,235 acres of ponderosa pine stands, and removing approximately 4.8 million board feet (mmbf) of thinned material as sawlogs or pulpwood between 1998 and 2001.

Figure 1 Vicinity Map and study site location



The study was an operational experiment with a replicated block design consisting of four blocks and four treatments. The treatments were thin, burn, thin and burn, and control. The thin treatment employed mechanized cut-to-length harvesting systems using single-grip harvester and forwarder combinations to reduce the merchantable overstory (live and standing dead) and down and dead material. The burn treatment used an understory burn technique in stands without any pre-treatment of fuels and was conducted using handheld drip torches. The thin and burn treatment combined a mechanized harvest followed by an understory burn using both of the above techniques. The control treatment will be used to compare future stand development over time.

Sixteen experimental units were selected and randomly assigned to a given treatment (Table 6). Prior to selection, 164-ft, permanent, fixed radius sampling plots were located on transects at 328-ft intervals in homogenous stands within similar vegetation types. These plots were used as sampling points or hubs for a variety of data collected over the study by the interdisciplinary team members (fire intensity, fuel loading, stand structure, etc.).

While there was variation within each unit (i.e., past commercial thinning, dense patches of small diameter trees, and open rock scabs), the variation among units was relatively small. The plant associations for the units were *Pseudotsuga menzeseii/Symphocarpus albus* (PSME/SYAL) and *Pinus ponderosa/Symphocarpus albus* (PINO/SYAL). Stand density index (SDI) and basal area (BA) were determined for the pre-treatment conditions and the total and forested area was determined from aerial photos. The pre-harvest quadratic mean diameter (QMD) ranged from 9 to 11 inches with an average of 10, and ranged from 12 to 15 inches post-harvest with an average of 13.4 inches. Summaries of initial stand condition and post-harvest stand conditions for the thinned units can be found in Table 7. Range of percent slopes, average aspect, and average skidding distance are shown in Table 8. The average skidding distance for all units was 933 feet.

A photo series of the study units shown in Table 6, 7, and 8 and Figure 2 can be found in the appendix. These photos show the progression of treatments (over time) from a single photo point location in each unit.

Table 5 Plant association, initial stand conditions, number of sample plots and assigned treatment for the 16 experimental units.

Harvest Unit	Plant Association	SDI[1]	BA (ft^2)	Forested Acres	Total Acres	Number of Sample plots	Treatment
2, 4, 5	PSME/SYAL	233	122	17	35	21	Control
6A	PSME/SYAL	214	113	29	29	26	Thin
6B	PSME/SYAL	186	103	27	27	29	Thin and Burn
7	PSME/SYAL	267	145	43	54	25	Thin
8A	PIPO/SYAL	210	114	40	40	23	Thin and Burn
8B	PIPO/SYAL	210	114	40	40	23	Burn
9	PSME/SYAL	190	107	80	134	23	Thin
10A	PIPO/SYAL	181	105	40	40	24	Thin and Burn
10B	PIPO/SYAL	181	105	70	70	21	Burn
11, 12	PIPO/SYAL PSME/SYAL	171	98	31	54	35	Thin and Burn
15	PSME/SYAL	178	102	40	68	20	Control
18	PSME/SYAL	218	120	20	20	20	Control
21	PSME/SYAL	211	112	33	36	30	Burn
22	PSME/SYAL	181	102	51	95	28	Thin
23	PSME/SYAL	230	128	77	162	28	Control
24	PIPO/SYAL PSME/SYAL	228	123	40	76	23	Burn
Mean	N/A	206	113	42	61	25	N/A
All	N/A	N/A	N/A	678	980	400	N/A

[1]Site density index (SDI) is the equivalent number of 10 inches trees per acre.

Table 6 Initial stand conditions and post harvest stand conditions for quadratic mean diameter (QMD) and trees per acre (TPA).

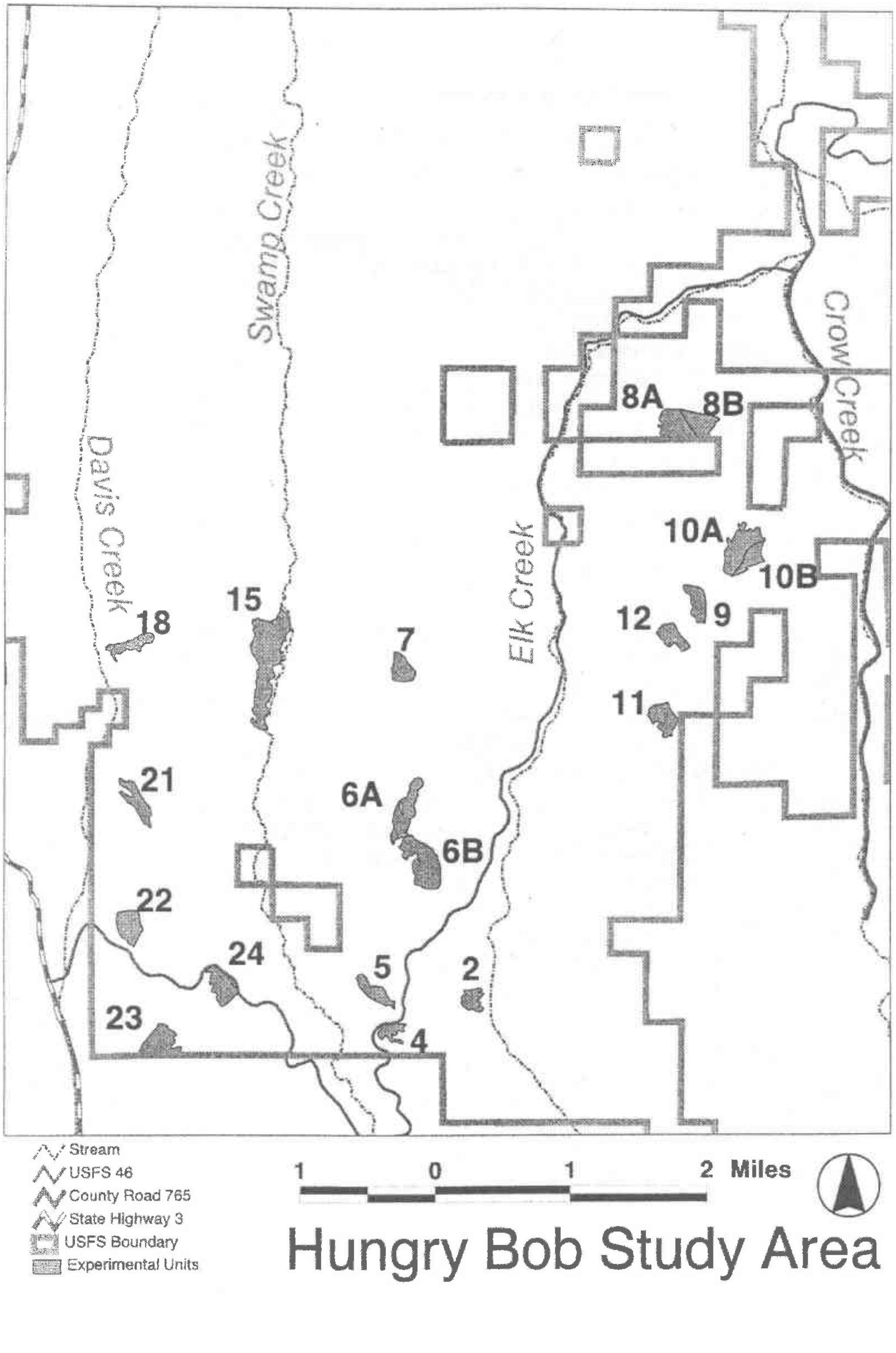
Harvest Unit	Initial QMD (Inches)	Initial TPA	Post Harvest QMD (Inches)	Post Harvest TPA	Treatment
2, 4, 5	11	200	N/A	N/A	Control
6A	9	253	13	81	Thin
6B	9	220	13	81	Thin and Burn
7	9	316	13	64	Thin
8A	11	180	14	54	Thin and Burn
8B	11	180	N/A	N/A	Burn
9	10	190	14	61	Thin
10A	10	181	13	67	Thin and Burn
10B	10	181	N/A	N/A	Burn
11, 12	10	171	12	74	Thin and Burn
15	10	178	N/A	N/A	Control
18	9	258	N/A	N/A	Control
21	10	211	N/A	N/A	Burn
22	11	155	15	48	Thin
23	10	230	N/A	N/A	Control
24	10	228	N/A	N/A	Burn
Mean	10	208	13.4	66	N/A

Table 7 Terrain conditions for treatment.

Harvest Unit	Minimum Percent Slope	Maximum Percent Slope	Average Percent Slope	Average Aspect (Azimuth)	Average Skidding Distance[1]	Treatment
2, 4, 5	3	20	11	201	N/A	Control
6A	1	27	11	282	950	Thin
6B	6	27	16	210	1050	Thin and Burn
7	8	32	21	310	800	Thin
8A	2	15	9	266	900	Thin and Burn
8B	3	14	8	96	N/A	Burn
9	7	20	12	51	825	Thin
10A	2	25	13	296	900	Thin and Burn
10B	1	22	8	170	N/A	Burn
11, 12	0	20	10	290	750	Thin and Burn
15	3	27	18	108	N/A	Control
18	13	40	26	296	N/A	Control
21	11	28	18	231	N/A	Burn
22	2	20	8	272	1200	Thin
23	1	18	10	234	N/A	Control
24	1	28	9	98	N/A	Burn
Mean	4	24	13	213	922	N/A

[1]Average skidding distance in feet for one-way travel.

Figure 2 Hungry Bob study area map and treatment unit location.



Desired Future Conditions

Short-term desired future conditions of stands after the initial set of treatments guided silvicultural and prescribed fire prescriptions (McIver et al. 1997). In the thin only, with mechanized cut-to-length systems, trees were marked to take with a target to reduce basal area from about 120 ft^2/acre to about 70 ft^2/acre. In addition, the prescription was to leave dominant and codominant crown classes, accept wide distribution in space to account for natural clumps, retain all old live trees greater than 21 inches DBH, and remove competing conifers within 30 feet (9 meters) of dominants to prolong structural characteristics. The prescriptions were targeted to leave 70 to 80% of the pretreatment ponderosa pine and 60 to 80% Douglas-fir.

Harvest System and Prescribe Fire Equipment

Three distinctly different harvesters all equipped with a single-grip harvester head were used in the felling and processing of all material in the study area. These machines (Table9 and Figures 3-5) were a Rottne SMV Rapid EGS, John Deere 653E, and Caterpillar 320L excavator. Three different forwarders were used as well. These machines (Table 9 and Figure 6-8) were a Timbco TF815-C, Rottne SMV Rapid, and Rottne Rapid. Logging of all thin and thin and burn treatments were conducted in summer 1998.

Table 8 Harvester and forwarder equipment specifications.

Equipment Specifications	Single-grip Harvester			Forwarder		
	Rottne SMV Rapid EGS	John Deere 653C	Cat 320L Excavator	Timbco TF815-C	Rottne SMV Rapid	Rottne Rapid
Identification Name	Rottne	John Deere	Cat	Timbco	Rottne SMV	Rottne Rapid
Tire/Track	6-Wheel drive	Tracked	Tracked	8-Wheel drive	6-Wheel drive	6-Wheel drive
Head Type	EGS 600	Waratah HTH Warrior	Keto 500	N/A	N/A	N/A
Capacity Max diameter or Max payload	23.6 in.	22.0 in.	29.5 in.	16 ton	12 ton	10 ton
Bogie Location	Rear	N/A	N/A	Front and Rear	Rear	Rear
Max Boom Reach	32.8 ft.	23.5 ft.	Data not available	24.75 ft.	31.4 ft.	28.9 ft.
Machine Weight (unloaded)	15.1 tons	18.3 tons	25.3 tons	20.3 tons	15.3 tons	12.0 tons
Operator Experience (years)	3+	3+	3+	3+	3+	< 1 & 3+[1]

[1]Two operators with different experience levels operated the Rottne Rapid (percent time spent by operator with < 1 year was 80% and the operator with 3+ year was 20%)

Figure 3 Rottne SMV Rapid EGS with EGS 600 harvester head, single-grip-harvester.

Figure 4 John Deere 653C with Waratah HTH Warrior, single-grip-harvester.

Figure 5 Caterpillar 320L Excavator with Keto 500, single-grip-harvester.

Figure 6 Timbco TF815-C, 16-ton forwarder.

Figure 7 Rottne SMV Rapid, 12-ton forwarder.

Figure 8 Rottne Rapid, 10-ton forwarder.

Prescribed Fire Lighting Crews

On file at the Wallowa Whitman National Forest, Wallowa Valley Ranger Station, in Enterprise, Oregon is the Prescribed Fire Burn Plan for the Hungry Bob project. The protocol or standard mode of operation administered by the Wallowa Valley Ranger District in 1998 was followed. While researchers were present on site, their involvement and conduct with the lighting crews, holding crews and administrators was by observation only.

All prescribed fire treatments were carried out with hand-carried drip torches with a mix of diesel and gas (Figure 9). Typically, a crew consisted of a Burn Boss, Lighting Specialist, Holding Specialist, and 10-15 Lighters and Holders. On site the crews were supported by 1 or 2 fire engines, which had limited involvement in conducting the burn.

All prescribed fire crewmembers were qualified to perform their assigned duties through training conducted by the USDA-Forest Service. All Burn Bosses, Lighting Specialists, and Holding Specialists went through a series of classroom courses and field training in order to become certified to perform their roll. All of the supervisors and many of the crew members were experienced veterans in prescribed fire as well as fire suppression. All burn and thin and burn treatments were broadcast burned during August 2000.

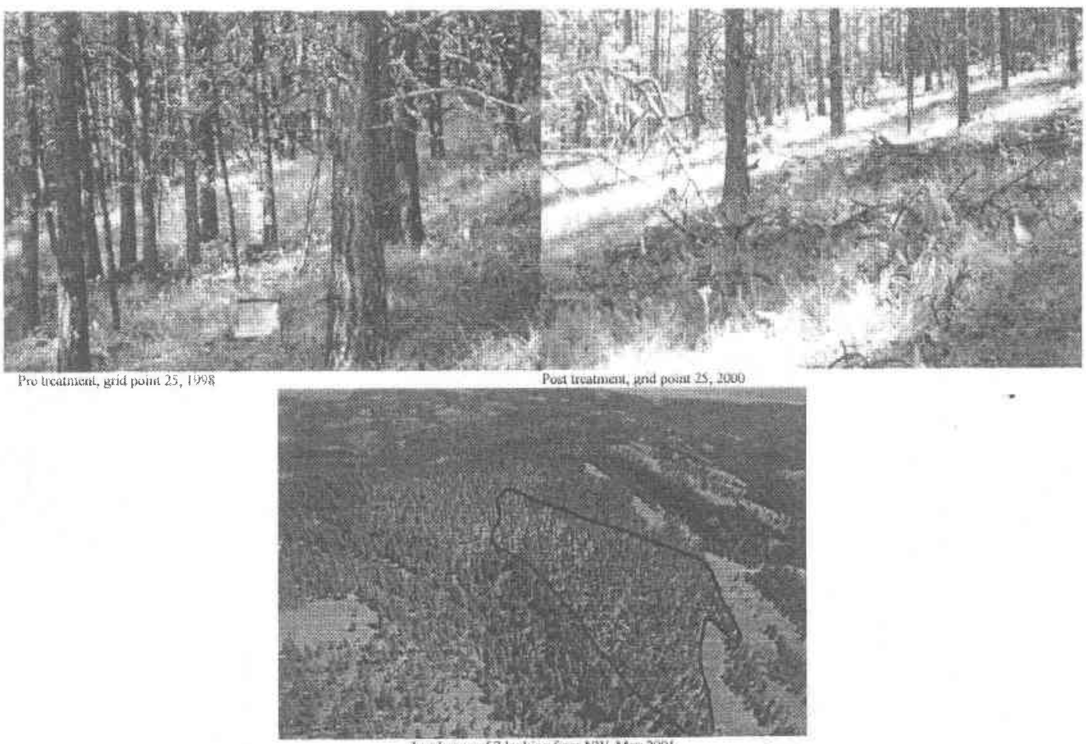
Figure 9 Prescribed lighting crew using hand held drip torches igniting Thin and Burn unit 12.

Photo Series of Treatments

The following time series of photos (Figures 10 to 12) show selected units and treatments. Photos were taken by members of the Fire, Fire Surrogate (FFS) Study. All other photo series can be found in the Appendix A.

Figure 10 Thin only treatments at unit 7.

Hungry Bob FFS Study Unit # 7



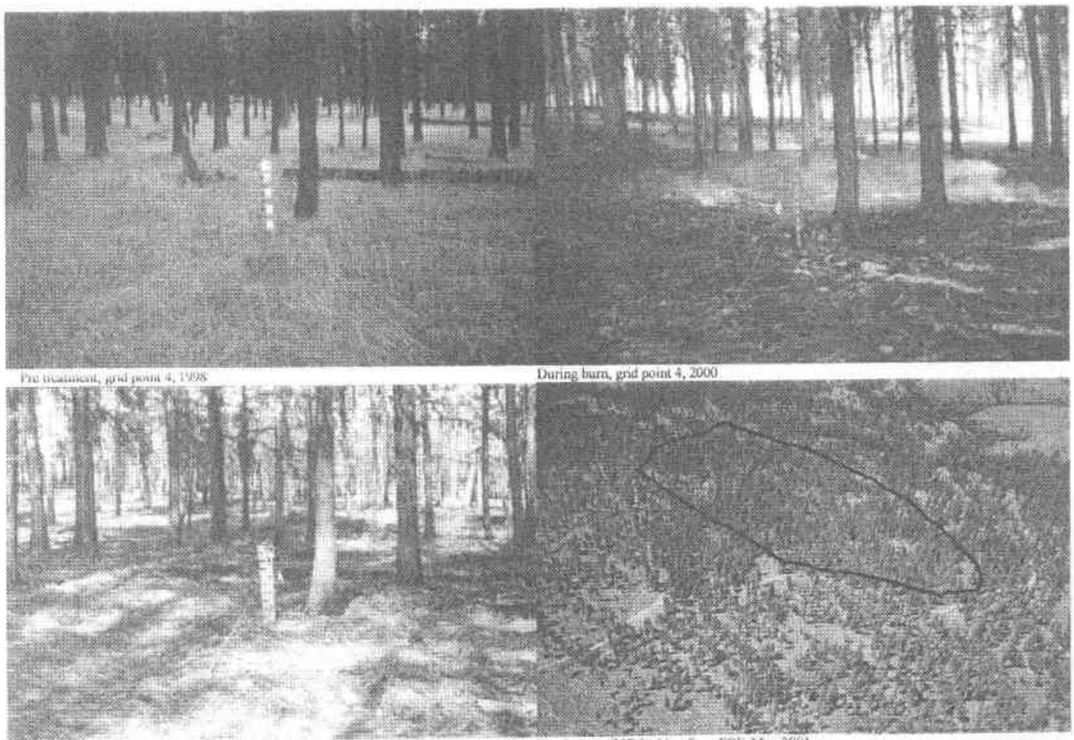
Pre treatment, grid point 25, 1998

Post treatment, grid point 25, 2000

Landscape of 7 looking from NW, May 2001

Figure 11 Burn only treatment at unit 8B.

Hungry Bob FFS Study Unit # 8B



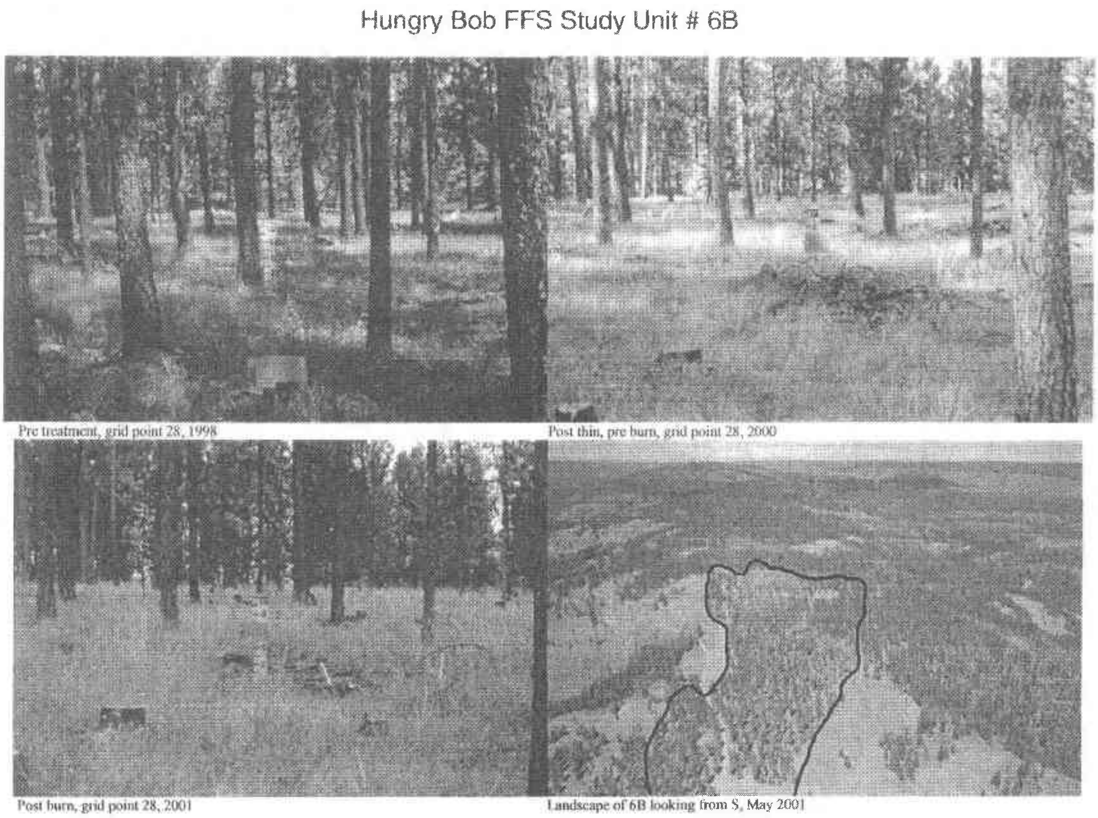
Pre treatment, grid point 4, 1998

During burn, grid point 4, 2000

Post burn, grid point 4, 2000

Landscape of 8B looking from ESE, May 2001

Figure 12 Thin and Burn treatment at unit 6B.



Methods

Treatment Costs and Production

Determining machine performance requires accurate production data. Collecting such production data is challenging because of the variability within the forestry environment (Olsen and Kellogg 1983). The study methods that were used (shift level and detailed time studies) allowed for calculating productive and non-productive time, breaking down productive time into cycle elements, and calculating interactions between equipment, personnel, and harvesting attributes.

Shift level studies are daily production averages based on observer or worker records of pieces handled and hours worked (Olsen and Kellogg 1983). Each equipment operator was given a daily production form that was completed at the end of every shift. The production form included items such as location, hours worked, delays, and production information (see Appendix E for example shift level forms).

With the use of small hand-held computers or data collectors, it has become easier to conduct detailed time studies. With this technique, the times and conditions for each turn (sequence of activities required to bring a group of logs or trees to the landing) are recorded (Olsen and Kellogg 1983). Cycle components are timed, delays are broken out with their causes, and independent variables (i.e., logs per turn, skidding distance, etc.) are recorded. This data is used to generate the regression model for a sequence of cycles. A Husky Hunter (Husky Computer Limited 1989) was used along with the program, Siworks 3 (Danish Institute of Forest Technology 1988) to conduct the detailed time study.

Mechanical Harvesting Data Collection

A combination of detailed time and shift level time studies was used to gather data on production for both the harvesters and forwarders. Shift level data was collected over the entire study area for all harvesters and forwarders. The detailed data was collected at random for the three harvesters and forwarders as they progressed from one harvest unit to the next. Turn cycles were broken down into individual elements for the harvester and the forwarder (definitions of cycle time elements can be found in Appendix D)

The cycle for the harvester was broken down into the following components:

Dependent Variables:

- Travel to the tree (move)
- Cut and process the tree into log lengths (process)

Independent Variables:

- Tree diameter at the stump in inches
- Tree species, ponderosa pine or Douglas-fir
- Tree position, live, standing dead, or down dead

    - Live had at least one green limb
        - Standing dead had no green limbs and was positioned at an angle greater than 45 degrees, with respect to the ground
        - Downed was either severed at the base or had no green limbs and was positioned at an angle less than 45 degrees, with respect to the ground
- Travel distance in feet, one-way

Delays (for both harvester and forwarder):

- Maintenance
- Mechanical delay
- Personal delay
- Other delay

The following was also noted within each detailed time study file (for both harvester and forwarder):

- Date
- Unit
- Start time
- Operator

The cutting and processing of one stem (standing or downed) designated a timed cycle. This included any movement of the stem as well as any delays. Travel time started when the harvester released the last stem and moved toward the next stem to cut. Travel time ended when the harvester first grabbed a stem. Cut times started when the harvester grabbed a stem 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 cycle ended.

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

Dependent Variables:

- Travel Unloaded
- Load
- Travel Loaded
- Unload

Independent Variables:

- Number of stops to load
- Number of pulpwood pieces unloaded
- Number of sawlog pieces unloaded

Cycles 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 (combined with unload) once the forwarder returned to the landing as well as any delays that occurred during travel loaded and unloaded. 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 pulpwood pieces was recorded. Travel loaded was the time it took to move to the next deck of logs and travel to roadside when fully loaded. 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.

At the end of each shift, the operator filled out a shift level report. All shift level reports contained the following information:

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

The harvester shift-level reports contained the following information in addition to the above:

- Total pieces
- Sawlog pieces
- Pulpwood pieces

- Total trees
- Sawlog trees
- Pulpwood trees

The forwarder shift-level reports also contained additional information, including:

- Number of loads for the day
- For each load
    - Percent green volume on each load
    - Where sorting occurred (woods, landing, or both)

Percent green volume was visually estimated by the operator. While subjective, the data was gathered as a back up to scale ticket harvest data. A sample of the harvester shift-level report can be found in Appendix E.

Determining Material Removed

Scale ticket information provided by the USDA-Forest Service and results of the detailed time study were used to determine the species mix, log grade, and volume removed from the study area. All log truck loads taken to the mill were weight-scaled. A portion of loads delivered to the mill was rolled out and scaled with individual species and their gross and net board foot measurements taken. This information was used to determine the board foot (bf) to weight ratio for all loads. A total of 44 loads from the 439 loads delivered to the mill were scaled giving a 10% sample size. Log truck loads were primarily sorted by either sawlogs or pulpwood and delivered to the mill with as mixed species (ponderosa pine and Douglas-fir). Value was determined from the delivered price to the mill, and at the time of the study (1998) it was $55/ton and $20/ton for sawlogs and pulpwood, respectively.

Prescribed Fire Data Collection

The time studies that were performed on the prescribed fire portion of the study were conducted similarly to those used for the harvester and forwarder. However, a modification of the standard activity sampling method was used. Activity sampling measures the proportion of the workday that individual machines and people spend at each of a series of activities. In addition, it also measures the interactions of equipment and personnel. Observations can be made at random times or at equally spaced intervals. The latter technique is called fixed-intervals, systematic, group-timing, or multi-moment sampling (Olsen and Kellogg 1983). The activity sampling technique that was used was the fixed-interval or multi-moment sampling. The fixed interval method is an acceptable method because of the variability in a forestry operation (Olsen and Kellogg 1983).

The standard activity sample was merged with a detailed time study to produce what will be referred to as a detailed activity sample or fixed-interval detailed time study. Rather than a set of steps or procedures determining the starting and ending point of a cycle, a hypothetical cycle time of 10 minutes defined a fixed-time interval. Unlike activity sampling where the observer records the operation at a given time interval, the observer continuously recorded the operation's dependent and independent variables for the given interval of time. The following is a list of variables that was collected during each interval.

Timing Variables:

- Planning (communication with crew or supervisor)
- Lighting
- Holding
- Traveling within unit
- Traveling by vehicle to and between units
- Preparing equipment (i.e. filling drip-torches)

Delays:

- Idle (i.e., personal break, waiting for instructions, and any non-burn activity)

The following was also recorded for the detailed time:

- Date
- Unit
- Start time
- End time
- Operator

A shift level study was also conducted on all personnel involved in conducting the burn. Standard Wallowa Valley Ranger District forms (Appendix E) were used to monitor hours and time spent by personnel in the different activities associated with the controlled burn. In addition, vehicle mileage and equipment costs were recorded. Shift level data for the prescribed fire treatment included the actual costs and wages for individual USDA-Forest Service personnel who conducted the burn.

Prescribed fire intensity was measured at each plot center for all units being treated with prescribed fire. Flame temperatures were determined by using heat-sensitive indicator paint applied to ceramic tiles (Omega Engineering, Inc.) suspended 1 foot and 4 feet above the forest floor (Figure 13). Heat sensitivities ranged from 40 to 900° C, at approximately 20° C intervals between 40 and 400° C and 75° C intervals for > 400° C (Figure 14 and 15). When threshold temperatures were reached during burning for each level of sensitivity, melted paint indicated the temperature exceeded the threshold temperature but was lower than the next threshold temperature.

Figure 13 Heat tile located at a plot center in Thin and Burn treatment unit.

Figure 14 Heat tile with heat sensitive paint prior to exposure.

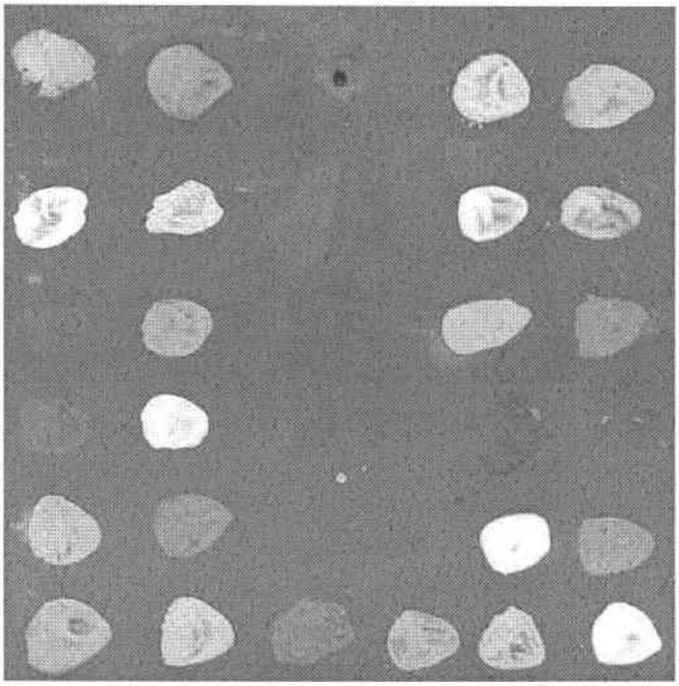
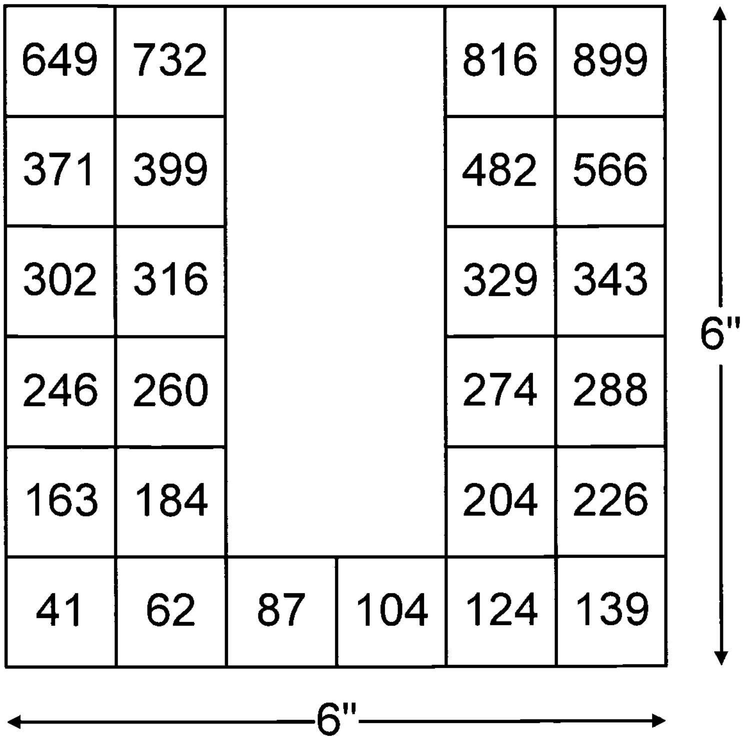


Figure 15 Temperature in degrees Celsius for heat sensitive paint with location on heat tile.



The ceramic tile was a standard 6"x6" red cinder tile purchased at a local hardware store. It should be noted that the threshold temperature recorded for each plot was not an absolute, but rather a relative measure among the units. The reaction time of the heat sensitive paint was reported to be near six microseconds. However, due to the time it took for the tile to react to the temperature being applied, an absolute maximum was not found. Through tests conducted on the tiles, it was estimated that the reaction time for temperatures below 260 degrees Celsius was approximately 5 seconds. Reaction time for temperature over 260 degrees Celsius was estimated at 10 seconds. This means that a moving or wind-blown flame may not have the residence time to activate the paint.

Statistical Analysis

Using Statgraphics (Manugistics, Inc. 1995), descriptive statistics were constructed for the stand conditions, shift level time studies, and detailed time studies. Multiple linear regression was used to determine significances amongst variables affecting the production rates of mechanical thinning and prescribed fire. In addition, single and multi-factorial analysis of variance (ANOVA) was used to compare physical differences amongst prescribed fire intensity and associated variables. These methods and their output use are described below.

Descriptive statistics were used to analyze and report on standard conditions, machinery performance and cost, and prescribed fire intensity and cost. Mean values with their associated standard deviations and stand error values are reported throughout the paper. Descriptive statistics were used to determine average stand conditions and mean performance efficiencies for inclusion in the cost modeling procedure.

Multiple linear regression was used to construct predictive equations for mechanical thinning productivity (harvester and forwarder) and prescribed fire costs based on variables of influence. A significance level above the 95^{th} percentile was used to accept or reject a given variable and model. First, simple linear regression was used to investigate each coefficients affect on production time (basic scatter plot and p-value analysis). Transformations for each coefficient were then investigated to find better linear fit. Finally, all coefficients and their respective transformations were included into a multiple linear regression model and rejection and acceptances of the coefficients were determined by conducting a forward and backwards selection process. Correlation among coefficients was investigated by manual selecting different combinations of coefficients. This selection was based in part on experience with the data and random trials. Although causal relations based on correlation coefficients cannot be proven, it is possible to identify so-called spurious correlations; that is, correlations that are due mostly to the influences of "other" variables. For example, there is a correlation between the total amount of injuries or losses in a fire and the number of firefighters that were putting out the fire; however, what this correlation does not indicate is that if fewer firefighters were called to duty, then you could and probably would lower the injury and loss rate. There is a third variable (the initial size of the fire) that influences both the amount of injuries and losses and the number of firefighters. If this variable is controlled (e.g., consider only fires of a fixed size), then the correlation will either disappear or perhaps even change its sign (+ or -). The main problem with spurious correlations is determining what the "hidden" agent is. However, in cases where the variable is know, partial correlations that control for the influence of specified variables can be used.

Multiple liner regression models with the highest level of significance and containing no evidence of spurious correlations were selected and used for modeling productivity and cost. Incorporating the predictive equations into the cost model, sensitivity analysis was conducted using the equations by varying their coefficients.

Analysis of variance was used to determine the significances of prescribed fire intensity with respect to pretreatment of fuels. The single and multi-factorial ANOVA were used to test for a significant difference between the burn and thin and burn treatments between groups (burn and thin and burn) and within groups (treatment units). A significance level greater than the 95th percentile was used, however, due to a lower sample size between groups, a significance level above the 90th percentile would be appropriate given the variability of fire.

Cost Analysis and Model Construction

Detailed and shift level time study data was used to construct predictive equations for the harvester and forwarder. Costs were determined both for average stand conditions that occurred over all study units, as well as for individual study units using the conditions specific to those sites. Equipment productivity and cost was determined and then synthesized into the mechanical thinning and prescribed fire burn decision matrix.

Equipment Productivity and Cost

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

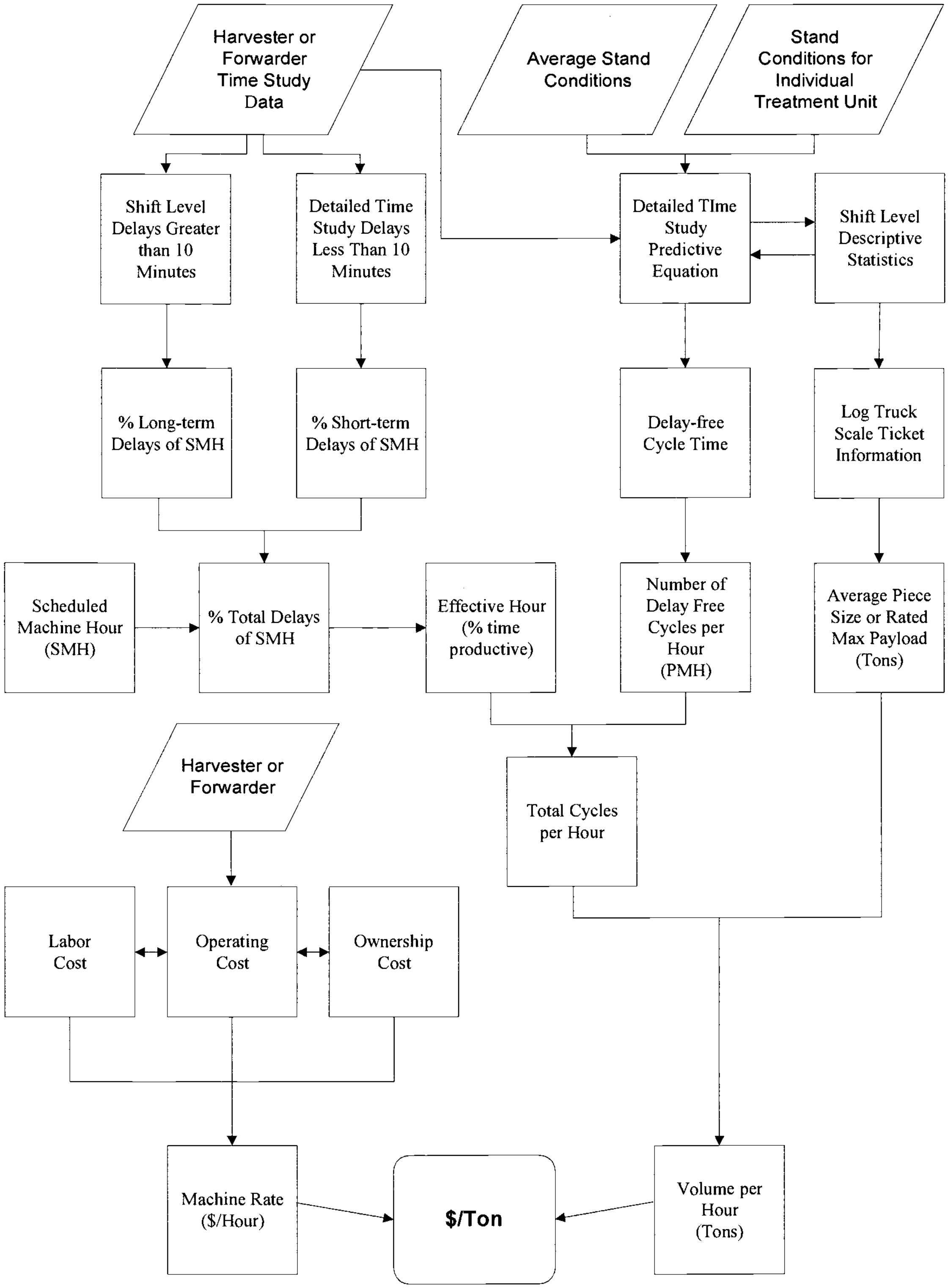
Costs per harvest unit of production cost for each machine were calculated by dividing machine rates by the corresponding production rate (Lambert and Howard 1990). Since all machines involved in the harvesting system had different production rates, all production costs were determined independently.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

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

After the owning and operating costs were derived from PACE, the following attributes were used to calculate individual machine costs. Multiple regression equations from the detailed time study were used to predict the cycle times. Long and short-term delays from the shift level and detailed time studies were calculated for individual equipment. A percent delay time was determined from both the shift level and detailed time studies. These percentages were then combined and a percent delay time per scheduled machine hour (SMH) was calculated. Finally, the rated payload for the forwarders were used to predict the average turn size as operators loaded to target their maximum design payload, however, individual piece size was used for the harvesters. The rated payload was the machine designed carrying capacity or payload. Average payload estimates for the forwarders were determined to be near the rated design payload as operators did not exceed the limits of the machines. The gross logging cost ($/ton) was determined for individual pieces of equipment by using the methodology shown in Figure 16.

Additional costs such as layout, loading (log trucks), hauling cost to the mill, support vehicles, and a 10% profit and risk were added to the cost of the harvester and forwarder. Layout and support were based on a per acre cost, and loading and hauling were based on the volume removed from each unit. Equipment rates were calculated by using PACE for the loader and the actual hourly cost was used for hauling the material to the mill.

Figure 16 Machine rate calculations and process flow chart for harvesters and forwarders.



Prescribed fire costs were determined by taking the information provided by the USDA-Forest Service in the shift level study. Personnel hours, assigned vehicle mileage, and quantity of supplies used were reported with their associated cost. Due to the variation in the actual reported hourly wages between personnel, a standardized wage was used depending on the duties preformed and individual workers. The Burn Boss (crew supervisor) was given a base wage of $25.00 per hour, Lighting and Holding Specialists were given a base rate of $20.00 per hour, and Lighting and Holding crewmembers received $10.00 per hour. To continue this standardization, all overtime was removed and charged at the base rate rather than time and a half. For information purposes the three prescribed fire costs were reported (actual cost, standardized cost with overtime, and the above standardized cost without overtime) but only the standardized rate without overtime was used for cost modeling and analysis.

Sensitivity Analysis

Sensitivity analysis was conducted using a cost model (discussed in the following section) developed from the predictive equations for the harvesters and forwarders. By its definition, sensitivity analysis measures the relative magnitude of changes in one or more elements of an economic comparison that will reverse a decision among alternatives (Riggs 1977). Further, sensitivity analysis is used to ascertain how a given model output depends upon the input parameters. This is an important method for checking the quality of a given model, as well as a powerful tool for checking the robustness and reliability of its analysis. The topic is acknowledged as essential for good modeling practice, and is an implicit part of any modeling field (Saltelli et al. 2001).

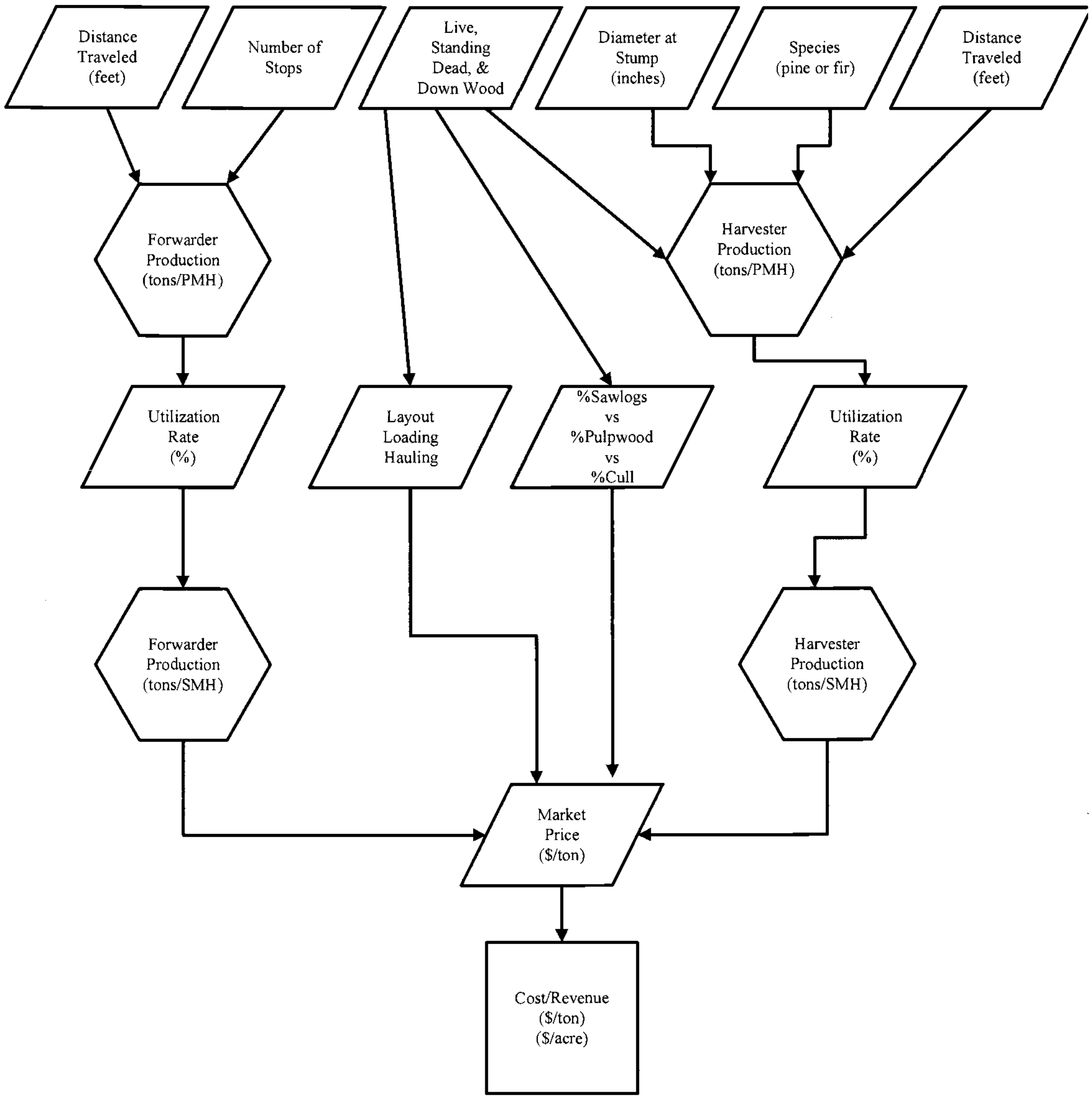
There are several possible procedures to perform sensitivity analysis. The most common sensitivity analysis, and the one used for this paper, is sampling-based. A sampling-based sensitivity analysis is one in which the model is executed repeatedly for combinations of differing input values. Through these repeated iterations the affect of a given input variable or variables can be determined. The following steps identify the basic process.

1. Develop a function equation using average conditions for the input variables (cost model).
2. Assign a distribution function to one or more input variables that changes that variable by some magnitude (linear functions were used in this anyalis).
3. Generate the output into a matrix of respective inputs with that distribution(s) through an iterative process.
4. Evaluate the effects of the input manipulation through graphical or statistical methods.

Model Simulations for Sensitivity Analysis

A cost model was constructed to conduct sensitivity analysis and investigate the component effects of different harvest conditions encountered on the study site and throughout the pine-dominated stands in the Blue Mountain region (Figure 17). The model was based on the data collected during this study. Average stand conditions encountered at the Hungry Bob study site were used as a base line to investigate stand and operational variables that effect the production and economics of commercial timber harvesting. Through this model, the amount of live tree, standing dead, and downed wood removal was modified and, using the predictive equations derived from this study, a harvesting production rate and associated cost were determined. The proportion of tree species removed (ponderosa pine and Douglas-fir) was varied, as well as average DBH for the different classes of wood removed (live, standing dead, and downed). In addition, the utilization rate for each machine, as well as loads per PMH and distance traveled for the forwarder were modified. The loading, hauling (secondary transportation), and profit and risk costs could also be modified (however in this paper only hauling was modified). Finally, market prices for delivered products were varied to reflect a change in value. The model returns cost in dollars per acre or dollars per ton and, depending on whether the market value is added, it returns the net loss and net profit in dollars per acre and dollars per ton.

Figure 17 Basic harvesting equipment productivity and cost model structure with inputs.



To conduct the sensitivity analysis, a series of iterations were run while selected key variables were changed with increasing or decreasing magnitudes and all other variables kept constant. As portions of the stand composition were manipulated, some variables in the cost calculations were related to each other and needed to be recalculated to predict the new production rates. These variables were individual tree volume, number of logs per tree and acre, and spacing of take trees or downed wood. For example, if the current stand has 30 tons per acre of downed wood with an average diameter of 6 inches, there would be 240 pieces of downed material or log segments (each weighing 250 lbs) that needed to be picked up from the forest floor, processed, and forwarded to the landing. If the average diameter of the downed wood removed was simulated to increase to 10 inches and the downed tons were left constant at 30 tons, the result would be fewer than 100 pieces at approximately 620 pounds a segment (a reduction in the number or density of downed wood log segments). A look-up table was created using regional volume tables for predicting height and volume from diameter. A weight per segment or tree was calculated by multiplying the volume times the unit weight of the respective class of material (live, standing dead, downed). Total tons per acre removed were divided by the tree or segment weight and the number of segments or trees per acre determined. The derived value for trees or segments per acre was assumed to be evenly distributed over the study unit and an average distance to travel from one stem to the next was calculated for the harvester and average skidding distance for the forwarder. These simulated values were then used to determine the harvesting production rates as the number of trees and segments per acre changed.

The interaction between the different machines and their associated costs was also introduced into the model. The 3 different harvesters and 3 forwarders that were paired at random throughout the study were simulated to work as an independent pair.

This produces a 3 by 3 matrix where nine different costs and/or revenues were determined. This comparison created a range of costs that were ranked from high to low. For the purpose of this report, the most cost-efficient harvester was paired with the most cost-efficient forwarder, followed by the second pair and then the third. These are labeled high, medium, and low and the respective machine rankings can be seen in Table 10.

Table 9 Productivity matrix for cut-to-length systems

	Relative Productivity	Harvester Type: Rottne	Harvester Type: John Deere	Harvester Type: Cat
Forwarder Type	Timbco	High	-------	-------
Forwarder Type	Rottne SMV	-------	Medium	-------
Forwarder Type	Rottne Rapid	-------	-------	Low

Mechanical Thinning and Prescribed Burn Decision Matrix

The model simulation and sensitivity analysis output was used to help formulate a decision-making process along with the cost to use prescribed fire. Four common stand types that occur in and around the study units were identified (open, average, downed woody concentration, and dense stand). These stands span a basic range of stocking levels, material composition for removal, and downed woody fuels that typically occur over the area.

By synthesizing and interpreting the sensitivity analysis data, cost estimates were provided for different treatment scenarios using mechanical thinning, prescribed fire, or thinning and burning together. A framework was created to guide this analysis, which is presented in the Discussion section.

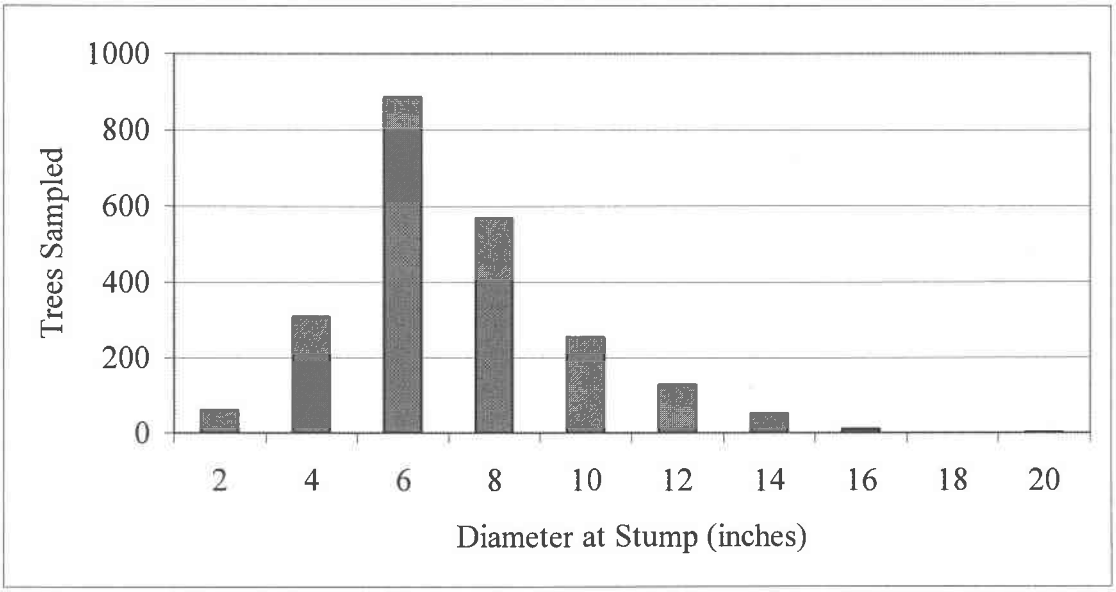
Results

The predictive equations used to compare machine performance were based on individual machines and average stand conditions that occurred over all harvest units. However, data from individual stands was used to calculate treatment costs by unit.

Material Removed in Thin Treatment

Two main tree species made up almost 100% of all material removed. Ponderosa pine comprised 70% and Douglas-fir 30% of either sawlogs or pulpwood. Due to the limited quantities of other species (<1%), all non-ponderosa pine species were counted as Douglas-fir. The average number of trees per acre removed was 142 (Table 7). The diameter distribution shown in Figure 18 was derived from stems removed from the harvesters' detailed time study that was a random sample of 2266 observations over the entire study area. An average diameter of 7.1 inches at the stump was calculated.

Figure 18 Diameter distribution for stems removed from all harvest units.



Tons removed per acre for the individual treatment units are shown in Table 11 (Dodson-Coulter 1999), and the breakdown of material type removed for individual units in Table 12. A difference in tons per load was due to the payload capabilities of the three forwarders as they worked through the study units. The log truck load characteristics data for the rollout scale information collected at the mill is shown in Table 13.

Table 10 Forwarder loads by unit, tons removed per unit, and average ton per load per unit for sawlogs and pulpwood.

Unit	Sawlogs			Pulpwood		
	Forwarder Loads	Tons/Unit	Tons/Load	Forwarder Loads	Ton/Units	Tons/Load
6A[1], 6B[2]	94.9	942.4	9.9	50.1	591.7	11.8
7[1]	83.8	845.3	10.1	29.2	414.4	14.2
8A[2]	112.2	1637.0	14.6	38.8	467.8	12.1
9[1]	125.9	1534.5	12.2	30.1	392.9	14.0
10A[2]	95.4	1081.8	11.3	30.6	322.2	10.5
11&12[2]	63.1	1082.5	17.2	19.0	329.9	17.4
22[1]	63.0	660.43	10.5	42.0	333.0	7.9
TOTAL	638.3	7783.9	12.2	239.8	2851.9	11.9

[1]Thin treatment.
[2]Thin and burn treatment.

Table 11 Amount of material removed in tons per acre by type (live, standing dead, downed, and all).

Unit	Acres	Tons Removed per Acre			
		Live	Standing Dead	Downed	All
6A[1],6B[2]	56	31.4	2.0	0.3	33.7
7[1]	43	27.3	1.7	0.2	29.3
8a[2]	40	49.1	3.1	0.4	52.6
9[1]	80	22.4	1.4	0.2	24.1
10A[2]	40	32.7	2.1	0.3	35.1
11&12[2]	31	42.5	2.7	0.3	45.6
22[1]	51	18.1	1.2	0.2	19.5
TOTAL	341	29.1	1.9	0.2	31.2

[1]Thin treatment.
[2]Thin and burn treatment

Table 12 Log truck load characteristics from rollout scale information collected at the mill.

Log Truck Load Characteristics	Gross bf/load	Net bf/load	Tons/load	Gross bf/ton	Net bf/ton
Mean	4390.9	3817.7	28.7	152.8	132.9
Standard Deviation	322.4	646.4	1.7	13.1	23.5
Number of Loads Sampled	44	44	44	44	44

Material was classified into either sawlogs or pulpwood. From the gross scale ticket information, 73% was sawlogs and 27% was pulpwood. A cull deduction of 13% was calculated for all loads giving a final breakdown of material removed to be 63.5% sawlogs, 23.5% pulpwood, and 13% cull. Since log truck loads were taken to the mill, mixed species and sort (camp run) cull and deduction was taken out for both sawlogs and pulpwood equally.

Machine Performance

Individual machine performance in the two treatments (thin and thin and burn) was calculated in productive machine hour (PMH) and scheduled machine hours (SMH) on an individual tree and per acre basis.

Harvester Performance

The average values for all timed elements for all harvesters in the detailed time study, are shown in Table 14.

Table 13 Average and standard deviation for time elements and significant variables in the detailed time study for all harvesters (100th of minutes).

Time Element	Process	Move	Distance Traveled (feet)	Diameter (Inches)	Delays			
					Mech.	Maint.	Pers.	Other
Mean	53.3	20.0	14.0	7.1	2.4	0.1	1.7	0.9
Standard Deviation	31.8	39.8	2.6	0.46	33.5	35.9	6.4	26.3

Multiple linear regression was used to develop predictive equations for the three different harvesters using the detailed time study data. All delays were removed from the data so PMH could be calculated. The derived models shown in Table 15, 16, and 17 were validated against a 10% portion of the detailed time study that was randomly selected and reserved (for each individual machine). No significant difference was found between predicted production rates and the reserved data sets (p-value of 0.94, 0.97, and 0.91 for the Rottne, John Deere, and Caterpillar, respectively).

Table 14 Regression model and associated statistics for processing time per tree by the Rottne harvester (100th of minutes). [1]

Parameter	Estimate	Standard Error	T Statistic	P-Value
Constant[2]	18.8	1.80	10.45	<0.0001
Standing Dead[6]	-15.5	4.29	-3.60	0.0003
Downed[6]	-21.7	2.92	-4.74	<0.0001
Species[3, 6]	4.8	2.21	2.16	0.0314
Distance Traveled[5]	1.2	0.02	55.12	<0.0001
Diameter*Diameter (at base)[4]	0.4	0.02	16.39	<0.0001

Analysis of Variance (Adjusted R^2 = 84.3%)

Source	Sum of Squares	Degrees Freedom	Mean Square	F-Ratio	P-Value
Model	2065559	5	413112	721.1	<0.0001
Residual	380379	664	573		

[1]Sample size n=670.
[2]Constant term includes live trees and ponderosa pine species.
[3]Species indicator for Douglas-fir (default ponderosa pine)
[4] Tree or log segment diameter at base in inches.
[5]Distance traveled in feet.
[6]Parameter is a 0,1 indicator.

Table 15 Regression model and associated statistics for processing time per tree by the John Deere harvester (100th of minutes). [1]

Parameter	Estimate	Standard Error	T Statistic	P-Value
Constant[2]	35.0	1.53	22.94	<0.0001
Standing Dead[6]	-10.7	3.50	-3.05	0.0024
Downed[6]	-30.4	10.19	-2.99	0.0029
Species[3, 6]	3.2	0.178	1.77	0.0077
Distance Traveled[5]	1.0	0.03	33.36	<0.0001
Diameter*Diameter (at base)[4]	0.5	0.02	23.15	<0.0001

Analysis of Variance (Adjusted R^2 = 62.3%)

Source	Sum of Squares	Degrees Freedom	Mean Square	F-Ratio	P-Value
Model	1252574	5	250514.8	349.3	<0.0001
Residual	753547	1052	716.3		

[1]Sample size n=1058.
Constant term includes live trees and ponderosa pine species.
[3]Species indicator for Douglas-fir (default ponderosa pine)
[4]Tree or log segment diameter at base in inches.
[5]Distance traveled in feet.
[6]Parameter is a 0,1 indicator.

Table 16 Regression model and associated statistics for processing time per tree by the Caterpillar, retro-fitted harvester (100th of minutes).[1]

Parameter	Estimate	Standard Error	T Statistic	P-Value
Constant[2]	42.6	2.99	14.27	<0.0001
Standing Dead[6]	-25.6	7.75	-3.31	0.0010
Downed[6]	3.8	1.54	0.25	0.0457
Species[3, 6]	8.5	3.20	2.65	0.0084
Distance Traveled[5]	1.1	0.05	19.88	<0.0001
Diameter*Diameter (at base)[4]	0.5	0.03	15.56	<0.0001

Analysis of Variance (Adjusted R^2 = 56.0%)

Source	Sum of Squares	Degrees Freedom	Mean Square	F-Ratio	P-Value
Model	784215.9	5	156843.2	137.7049	<0.0001
Residual	607076.4	533	1138.98		

[1]Sample size n=539.
[2] Constant term includes live trees and ponderosa pine species.
[3]Species indicator for Douglas-fir (default ponderosa pine)
[4]Tree or log segment diameter at base in inches.
[5]Distance traveled in feet.
[6]Parameter is a 0,1 indicator.

Process and move times by the harvesters were the key time elements defining the overall cycle time. Table 18 reports the descriptive statistics with respect to the time in travel (move) or felling and processing a tree (process) for each harvester as well as for all harvesters.

Table 17 Descriptive statistics for cut and move time elements from the detailed time study (100th of minutes).

Parameter	Rottne		John Deere		Cat		All	
	Process	Move	Process	Move	Process	Move	Process	Move
Mean	40.9	18.5	52.6	20.5	70.1	21.0	53.3	20.0
Stnd. Dev.	24.7	52.7	29.5	31.8	36.2	35.0	31.8	39.8
Sample size	670		1058		539		2268	
Stnd. Error	0.96	2.04	0.91	0.98	1.56	1.51	0.67	0.84
Lower Limit (@95%)	40.0	16.4	51.7	19.5	68.5	19.5	---	---
Upper Limit (@95%)	41.9	20.5	53.5	21.5	71.6	22.5	---	---

A significant difference in the time it took the individual harvesters to process a stem was found between all harvesters using Fischer's (LSD) above the 95th% confidence level. The Rottne was the fastest of the three, followed by the John Deere and then the Caterpillar. A similar analysis was conducted on the time element move, but no significant difference was found between the means at the 95th %.

To investigate how stand conditions interacted with the different harvesters, standardized values were used for all harvest units and machines. Using these average stand conditions, the predicted PMH for each harvester was calculated. Ponderosa pine comprised 70% of the material removed and Douglas-fir 30%. The portion of live, standing dead, and downed material removed was 93.30%, 5.96%, and 0.74%, respectively with 31.2 tons per acre removed. An average diameter of 7.1 inches at the stump was used, along with a travel distance of 14 feet between processing locations. Table 19 shows the performance difference for processing the three different types of material removed from the thinned units (live, standing dead, and downed).

Table 18 Cycle time for individual harvesters by type of material (100th of minutes).

Parameter	Rottne	John Deere	Caterpillar
Live	53.5	73.0	84.5
Standing Dead	38.0	62.4	58.9
Downed	31.8	42.6	88.3

Using the average stand conditions, the following production rates and harvesting costs per acre were calculated for the three different harvesters (Table 20).

Table 19 Production rates, utilization, and operating costs for three harvesters in average stand conditions.

Production Measure	Rottne	John Deere	Cat
Cycle time per stem (minutes)	0.91	1.18	1.46
Stems per PMH	111.6	85.7	69.4
Utilization rate	65%	80%	80%
Stems per SMH	72.5	68.6	55.5
Acres/SMH	0.72	0.68	0.55
Hourly ownership and operating cost	$133.89	$130.48	$144.39
Cost/acre	$186	$193	$263
Cost/ton	$6.0	$6.2	$8.4

<u>Forwarder Performance</u>

Production for the three different forwarders was based on the shift level and detailed time study data. The shift level data has both short (< 5 minute) and long (> 5 minute) delays imbedded in it, but only the long-term delays reported separately. The detailed time study was conducted at random (based on machine availability within the study plots during a given day) on all machines as they operated through the harvest units. Due to the long cycle times associated with a typical forwarder, a total sample size of 42 cycles was determined for the detailed time study and included all harvest units and forwarders. Machines were analyzed together using multiple linear regression with indicator variables for the different machines. No significant differences were found between machines from the detailed time study. Table 21 reports the findings from the detailed time study.

Table 20 Regression model and associated statistics for forwarder cycle time for all forwarders (100th of minutes).[1]

Parameter	Estimate	Standard Error	T Statistic	P-Value
Constant	0.234	0.93	3.14	0.041
Distance[2]	0.009	0.0002	41.06	<0.0001
Stops[3]	0.332	0.02	15.45	<0.0001

Analysis of Variance (Adjusted R^2 = 76.2%)

Source	Sum of Squares	Degrees Freedom	Mean Square	F-Ratio	P-Value
Model	2519.2	2	1259.6	13816	<0.0001
Residual	12.2	39	0.314		

[1]Sample size n=42
[2]Measured in feet for distance travel by forwarder.
[3]Number of stops made by forwarder to load to capacity for roundtrip travel.

Table 22 reports the summary statistics for the significant variables used in the multiple linear regression analysis. In addition, the average travel time loaded and unloaded was reported along with the average of all delays.

Table 21 Summary statistics for significant variables found in the detailed time study for all forwarders (feet or 100th of minutes).

Parameter	Distance Traveled (feet)	Stops (number)	Travel Time (100th of minutes)	All Delays (100th of minutes)
Mean	2011.9	64.8	1784.8	336
Stnd. Dev.	677.9	11.8	853.8	41.3
Sample size	42	42	42	42
Stnd. Error	104.6	1.82	131.7	6.4
Lower Limit	1800.8	60.1	1500.1	323.1
Upper Limit	2223.1	67.5	2069.5	348.9

While the detailed time study found no significant difference between individual forwarders, the shift level data found a significant difference in the cycle times between the two Rottnes and Timbco forwarder. On a daily basis, using Fischer's LSD, differences between the mean number of loads produced by the Timbco were greater than those of the Rottne forwarders. It was found above the 95th% confidence level that the Rottne Rapid and Rottne SMV produced 0.24 loads per hour less than the Timbco. These significant findings, along with the regression equation from the detailed time study were used to conduct the cost modeling and sensitivity analysis for the forwarders production.

To determine production and associated cost, average stand conditions that affect forwarder production were calculated and used (Table 23). The average skidding distance for the forwarders was determined to be approximately 2000 feet and the average number of stops per roundtrip travel was 65. For the production and cost calculations, below, the actual forwarders' payloads were used and equal to their machines' designed payload capacity, and the average tons per acre removed of 31.2 was used.

Table 22 Production rates, utilization, and operating costs for three forwarders in average stand conditions.

Production Measure	Timbco	Rottne SMV	Rottne Rapid
Utilization Rate	89.0%	83.0%	80.0%
Load per PMH	1.47	1.24	1.24
Capacity (tons)	16	12	10
Load per SMH	1.31	1.03	0.99
Mean tons/acre removed	31.2	31.2	31.2
Acres/Hour	0.67	0.40	0.32
Hourly Ownership and Operating Cost	$100.63	$106.33	$94.07
Cost/Acre	$150	$266	$294
Cost/Ton	$4.8	$8.5	$9.4

Thinning Treatment Production and Cost

To complete the stump to mill cost calculations, planning, log truck loading, haul to the mill, and support costs were added into the equation. These values were derived from the average stand conditions as well as individual units. A layout cost of $50.00 per acre was used (Kellogg et al. 1998), and included office planning, boundary location, marking residual or take trees, and office analysis. The hourly log loader ownership and operating cost was calculated using PACE software. Using the scaling data and average stand conditions along cost for the loader ($73.05 per hour), a cost of $174.59 per acre was calculated for loading the log trucks. The trucking cost from the treatment units to the mill site was based on an average roundtrip time of 3.5 hours at a rate of $50.00 per hour (which included the ownership and operating cost of the vehicle). Using the scale information, with an average truckload of 28.1 tons, a cost of $196.17 per acre and $6.23 per ton was calculated. The total cost for layout, loading, and hauling was $420.76 per acre. Personal transportation to and from the job site and equipment shop costs were not included in the harvesting cost calculations.

To determine the harvesting cost for each treatment unit, the proportion of time that each individual machine spent in a unit was determined (Table 24). By using a weighted average of associated equipment costs and the proportion of time spent in a given unit, an actual harvest cost was determined. The percent time spent by individual machines was primarily due to the unit's location and adjacency to one another. Operators were allowed to select their next unit they traveled to and this was primarily based on proximity. Machines often traveled without the assistance of a lowboy tractor-trailer, unless they had to travel along a paved road. This limited transportation typically occurred at the end of a shift and was not included in the cost.

Table 23 Percent time working in treatment units by harvester and forwarder type.

	% Total Time Working in Unit					
Unit	Harvester			Forwarder		
	Rottne	John Deere	Cat	Timbco	Rottne SMV	Rottne Rapid
6A, 6B	44.5%	56.5%	-----	43.7%	56.3%	-----
7	53.8%	46.2%	-----	46.2%	53.8%	-----
8A	-----	-----	100%	100%	-----	-----
9	31.6%	31.6%	36.8%	31.6%	31.6%	36.8%
10A	-----	100%	-----	-----	-----	100%
11,12	-----	-----	100%	87.5%	12.5%	-----
22	-----	50.0%	50.0%	50%	-----	50.0%

Tables 25 and 26 show the production in PMH and SMH for the harvesters and forwarders as they worked in the respective units. The production rate with associated equipment and other added costs gives the average gross revenues per acre for the overall operation. These were calculated for individual units and also reported for all units reflecting the average stand condition (Table 27 and Figure 19). The net revenues per acre and ton were then calculated for each unit.

Table 24 Production by unit for harvesters and forwarders in tons/PMH

Unit	Production in Tons/PMH					
	Harvester			Forwarder		
	Rottne	John Deere	Cat	Timbco	Rottne SMV	Rottne Rapid
6A, 6B	35.0	26.7	-----	21.2	13.4	-----
7	33.9	26.2	-----	23.8	15.0	-----
8A	-----	-----	22.7	26.1	-----	-----
9	32.3	25.4	20.6	25.6	16.1	13.5
10A	-----	26.8	-----	-----	-----	11.2
11,12	-----	-----	22.4	29.0	18.3	-----
22	-----	24.6	20.0	22.7	-----	11.9

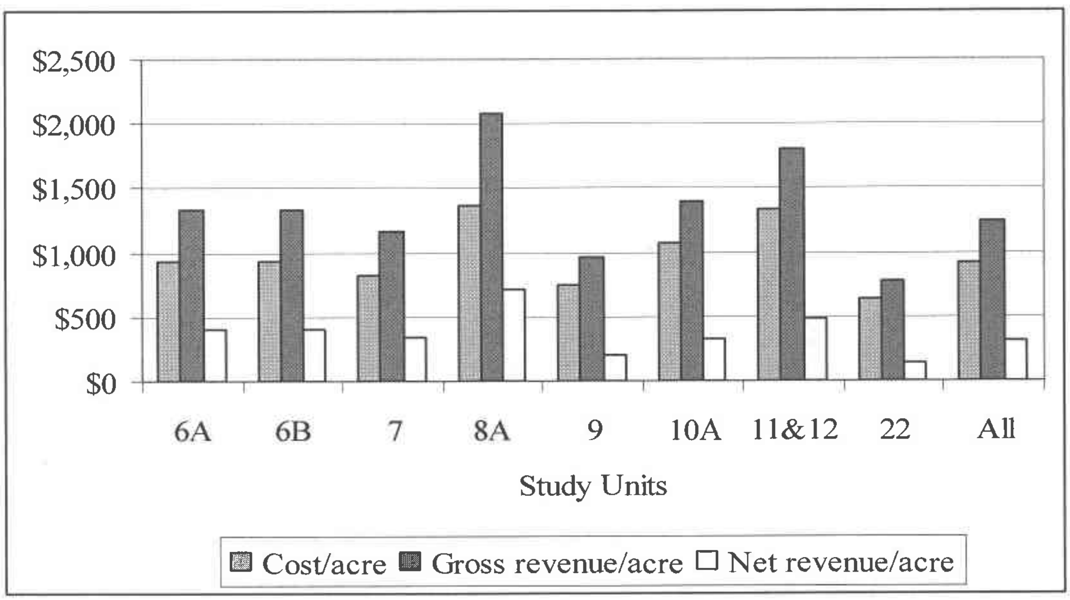
Table 25 Production by unit for harvesters and forwarders in tons/SMH

Unit	Production in Tons/SMH					
	Harvester			Forwarder		
	Rottne	John Deere	Cat	Timbco	Rottne SMV	Rottne Rapid
6A, 6B	22.7	21.4	-----	18.9	11.1	-----
7	22.0	20.9	-----	21.1	12.4	-----
8A	-----	-----	18.2	23.2	-----	-----
9	21.0	20.3	16.5	22.8	13.4	10.8
10A	-----	21.5	-----	-----	-----	9.0
11,12	-----	-----	17.9	25.8	15.2	-----
22	-----	19.7	16.0	20.2	-----	9.5

Table 26 Treatment unit cost, gross revenue per acre, and net revenue per acre and ton for harvest units.

Unit	Cost $/acre	Cost $/ton	Gross revenue $/acre	Net revenue $/acre	Net revenue $/ton
6A, 6B	928.74	27.59	1335	406.45	12.08
7	822.68	28.08	1162	339.48	11.59
8A	1369.61	26.03	2087	717.85	13.64
9	752.14	31.22	956	203.62	8.45
10A	1066.73	30.39	1392	325.70	9.28
11,12	1331.18	29.22	1807	476.26	10.45
22	629.72	32.33	773	143.02	7.34
All Units	921.89	29.56	1237	315.39	10.11

Figure 19 Cost and gross and net revenue per acre of mechanical harvesting of thin and thin and burn units.



Prescribed Fire: Thin and Thin and Burn Treatment Costs

Prescribed fire costs for both the thin and thin and burn treatments were calculated using shift level data. From the detailed time study, there was no significant difference between the portions of time spent in the different activities for the treatments (thin and thin and burn). This data is reported with summary statistics later.

With standardized pay rates for personnel and overtime removed, all personnel, vehicles, and supply costs were determined for each burn treatment (Table 28). Treatment units 8A, 8B and 10A, 10B were burned as single units and costs were broken out between the two treatment areas using the information from the detailed time study. While no significant predictive equation was derived from the detailed time study, it did provide the amount of time spent in the different units. In units 8A, 8B and 10A, 10B, the detailed study recorded equal time spent while conducting the burn in each unit. As a result, the treatment area cost for 8A, 8B and 10A, 10B was divided in half to separate them into individual units. Burn costs per acre were calculated using the total cost for a given treatment unit and divided by the total acres treated for that unit (Table 29). A total cost per acre for all treatments was found to be \$50.50 per acre. In comparison, using the actual costs that the USDA-Forest Service determined (which included individual pay rates and overtime) the cost of the average cost of the prescribed fire treatment was found to be \$61.18 per acre. Using the standardized pay rates outlined in the Methods section an average cost of \$60.10 per acre was found with overtime included.

Table 27 Component and unit costs for prescribed fire, thin and thin and burn treatments.

Unit	Treatment	Component cost ($/unit)			TOTAL ($/unit)
		Personnel	Vehicle	Supplies	
6B	Thin & Burn	2,080	95.4	99	2,274.4
8A	Thin & Burn	1,730	135.4	90	1,955.4
8B	Burn				
10A	Thin & Burn	2,300	123	72	2,495.0
10B	Burn				
11&12	Thin & Burn	2,495	95.4	117	2,707.4
21B	Burn	890	95.4	45	1,030.4
24	Burn	1,620	95.25	90.00	1,805.3
All Units		11,115	639.9	513	12,267.9

Table 28 Cost per acre for prescribed fire, thin and thin and burn treatments

Unit	Treatment	Treatment acres	Cost acres	Cost $/unit	Cost $/acre
6B	Thin & Burn	27	27	2,274.40	84.24
8A	Thin & Burn	40	69	1,955.40	24.44
8B	Burn	29			33.71
10A	Thin & Burn	40	61	2,495.00	31.19
10B	Burn	21			59.40
11&12	Thin & Burn	31	31	2,707.40	87.34
21B	Burn	26	26	1,030.40	39.63
24	Burn	29	29	1,805.25	62.25
All Units		243	243	12,267.85	50.50

Linear regression was conducted to determine if there was any relationship between treatment cost (burn and thin and burn) and the size (acres) of a treatment unit. Using a confidence level of 95%, no significance was found for a relationship between the cost per acre and treatment area (significance was found at a 79.1% confidence level, P-value of 0.21). To further investigate any area affect, treatment units were split into two groups delineated by a relative size to each other. Group 1 included all units between 21 and 31 acres (6B, 8B, 10B, 11&12, 21B, and 24) and group 2 included the two units that were 40 acres in size (8A and 10A). No significance was found at a 95% confidence level using a single factor analysis of variance. However, with a reported P-value of 0.091, there is a strong relationship between area treated and treatment cost between groups when the units were stratified into two groups.

To determine if there was any treatment effect on the prescribed fire costs a single-factor analysis of variance was conducted on the prescribed fire cost data. The units were broken down into burn and thin and burn treatments. No significant difference between the means at the 95% confidence level was found. A P-value of 0.67 was found with an average treatment cost of $48.75/acre (standard deviation 14.2) and $56.80/acre (standard deviation 33.6) for the burn and thin and burn treatments, respectively.

When the acres treated and treatment type was analyzed using multiple linear regression, a significant relationship was found that predicts the cost of prescribed fire (Table 30). The burn treatment was found to cost significantly less when acreage was included in the model and the variable acres found a significant reduction in cost as the size of the unit increased. While the units were randomly assigned there is some correlation with treatment type and the size of the unit. The thin and burn treatment areas averaged 34.5 acres per unit and the burn only averaged 26.3 acres per unit. The difference in average unit size (8.2 acres) therefore negates the treatment coefficient burn), making the magnitude of significance for the model a weaker relationship.

Table 29 Linear regression model predicting prescribed fire cost by acreage and treatment effect.

Regression Statistics	
Multiple R	0.84
R Square	0.70
Adjusted R Square	0.58
Standard Error	15.7
Observations	8

ANOVA

	df	SS	MS
Regression	2	2896.9	1448.5
Residual	5	1226.6	245.3
Total	7	4123.5	

	Coefficients	SE	t Stat	P-value	Lower 95%	Upper 95%
Intercept	195.28	41.97	4.65	0.0056	87.4	303.2
acres	-4.01	1.20	-3.36	0.0201	-7.1	-0.9
Burn[1]	-41.17	14.83	-2.78	0.0391	-79.3	-3.1

[1]Burn is a 0/1 indicator for thin = 0 and burn = 1.

In the detailed time study, no significant difference between treatments was found for production and time spent in different activities. P-values ranged from 0.8 to 0.4 for the different activities investigated in the detailed time study, and a P-value for the full and partial models ranged from 0.7 to 0.5; as a result, this data was not used in any analysis. The detailed time study does provided a breakdown of time spent in the different activities by a typical lighting and holding crewmember (Figure 20 and 21).

Figure 20 Time spent by a prescribed fire crewmember in different activities

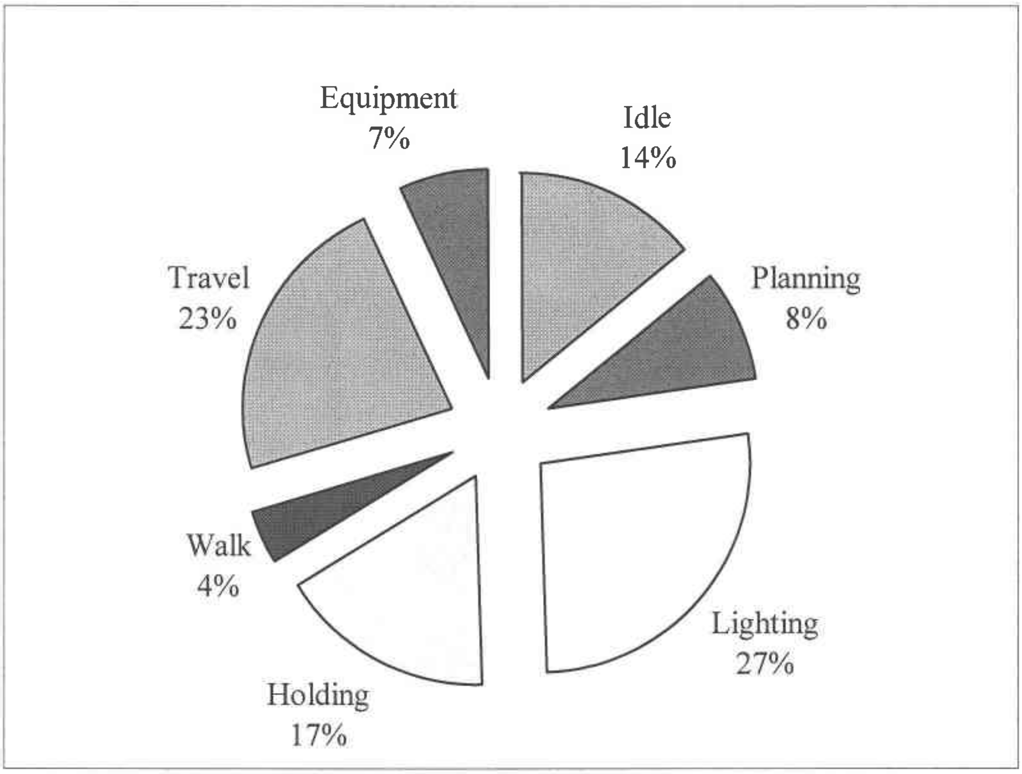
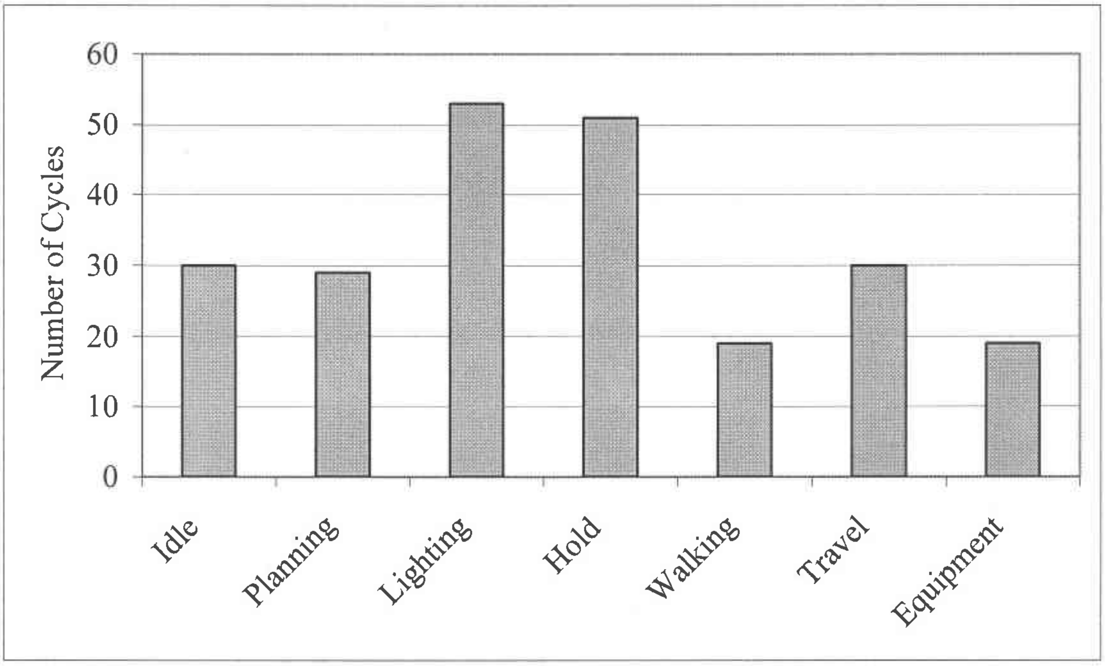


Figure 21 Number of 10-minute cycles in which the activity occurred with a total number of 107 recorded.



Total Treatment Profit or Cost

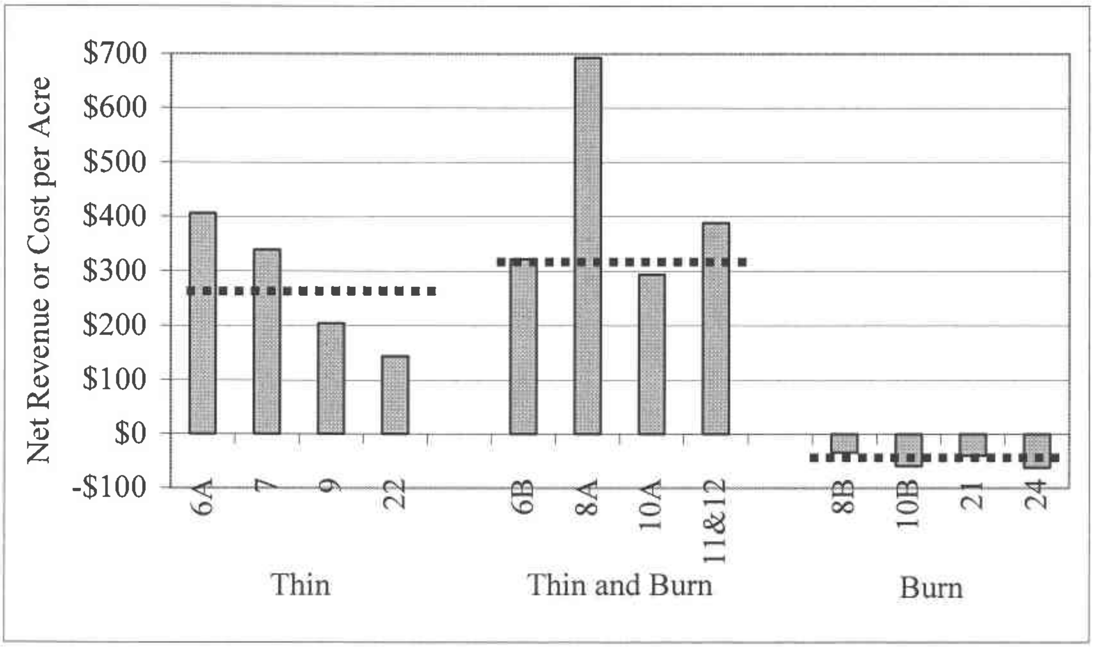
The total treatment profit or cost was calculated on a per acre basis. The average cost per acre was determined for each study unit (Table 31 and Figure 22), as well as an average value for all units within each treatment (Table 31).

Table 30 Total treatment profit or cost for burn, thin, and thin and burn

Unit	Treatment	Cost $/acre		Revenue $/acre	Profit or Cost $/acre
		Thin	Burn		
6A	Thin	928.74		1335	406.26
6B	Thin & Burn	928.74	84.24	1335	322.02
7	Thin	822.68		1162	339.32
8A	Thin & Burn	1369.61	24.44	2087	692.95
8B	Burn		33.71		-33.71
9	Thin	752.14		956	203.86
10A	Thin & Burn	1066.73	31.91	1392	293.36
10B	Burn		59.40		-59.40
11&12	Thin & Burn	1331.18	87.34	1807	388.48
22	Thin	629.72		773	143.28
21	Burn		39.63		-39.63
24	Burn		62.25		-62.25
Mean[1]	Thin	921.89		1237	315.12
Mean[1]	Thin & Burn	921.89	50.50	1237	264.63
Mean[1]	Burn		50.50		-50.50

[1]Mean values derived from total treatment cost for all units.

Figure 22 Net revenue or cost per acre by treatment (dotted line is mean value).



Prescribed Fire Intensity

Prescribed fire intensity is reported in Tables 32 and 33 for the burn and thin and burn treatments, respectively. Tile location is noted as lower for the one foot tile height and upper for the 4 foot tile height.

Table 31 Descriptive statistics for lower and upper heat tile data in burn treatment (units of measure in degrees Celsius).

	BURN							
Unit Tile	8b lower	8b upper	10b lower	10b upper	21 lower	21 upper	24 lower	24 upper
Mean	112.7	74.9	105.3	68.1	76.6	54.2	90.8	64.4
SD	61.7	46.0	66.9	35.0	57.3	38.3	102.2	78.3
N[1]	23	23	21	21	30	30	23	23
Max	246.1	204.4	301.7	138.9	204.4	124.4	315.6	260.0
Min	41.1	41.1	0	0	0	0	0	0
Zeros[2]	0	0	1	1	6	6	10	10

[1]Number of heat tile plots located in unit.
[2]Number of heat tile plots that recorded no temperature at the lowest heat threshold.

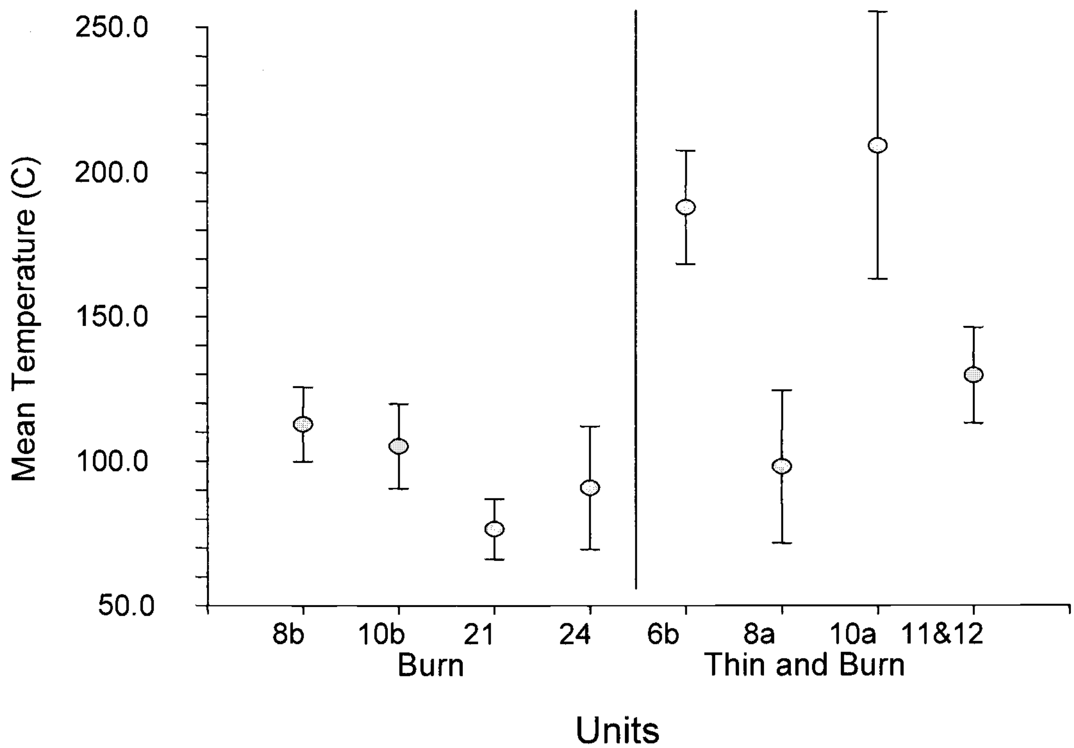
Table 32 Descriptive statistics for lower and upper heat tile data in thin and burn treatment (units of measure in degrees Celsius).

	THIN and BURN							
Unit Tile	6b lower	6b upper	8a lower	8a upper	10a lower	10a upper	11&12 lower	11&12 upper
Mean	187.9	93.5	98.1	50.8	209.3	116.4	129.9	90.7
SD	105.9	49.0	126.4	49.8	226.3	92.4	86.6	54.6
N[1]	29	29	23	23	24	24	27	27
Max	565.6	225.6	565.6	162.8	815.6	371.1	343.3	225.6
Min	0	0	0	0	0	0	0	0
Zeros[2]	1	1	6	6	2	2	2	2

[1]Number of heat tile plots located in unit.
[2]Number of heat tile plots that recorded no temperature at the lowest heat threshold.

The mean temperature achieved at the lower heat tile for the burn and thin and burn treatments is also shown in Figure 23. Standard error bars show the level of variability within each unit, as well as the relative differences among groups.

Figure 23 Mean fire intensity for the lower heat tile (1-foot) by unit with standard error bars.



A single factor ANOVA was conducted first by taking all the individual plot readings of temperature and grouping them into their respective treatments. A total of 97 plots were contained in the 4 burn units and 103 plots were contained in the 4 thin and burn units. A significant difference between the two treatments, based on reported temperature, was found at both the lower and upper heat tile height (Table 34 and 35). The variance about the mean at the lower tile height for the thin and burn treatment shows a considerably larger amount of variation over that of the burn treatment.

While the lower tile shows a large contrast, the upper tiles do not reflect the variability.

Table 33 ANOVA for lower heat tile for all plots (degrees Celsius).

SUMMARY

Groups	Count	Sum	Average	Variance
Burn lower	97	9190.6	94.7	5395.2
Thin & Burn lower	103	16237.8	157.6	21880.1

ANOVA

Source of Variation	SS	df	MS	F	P-value
Between Groups	197644.6	1	197644.6	14.23	0.0002
Within Groups	2749708	198	13887.4		
Total	2947353	199			

Table 34 ANOVA for upper heat tile all plots (degrees Celsius).

SUMMARY

Groups	Count	Sum	Average	Variance
Burn upper	97	6260.0	64.5	2651.5
Thin & Burn upper	103	9123.9	88.6	4391.4

ANOVA

Source of Variation	SS	df	MS	F	P-value
Between Groups	28883.0	1	28883.0	8.14	0.0048
Within Groups	702467.5	198	3547.8		
Total	731350.5	199			

Due to the randomized block design, a mean temperature was calculated for each treatment unit. A single factor ANOVA was run again for the lower and upper heat tile. A significant difference in the mean was found at the 0.0669 level for the lower heat tiles, while the upper tile was found to be statistically the same using a significance level of 0.1 (Tables 36 and 37).

Table 35 ANOVA of mean temperature for the lower heat tile by unit (degrees Celsius).

SUMMARY

Groups	Count	Sum	Average	Variance
Burn lower	4	385.4	96.3	255.3
Thin & Burn lower	4	625.2	156.3	2629.1

ANOVA

Source of Variation	SS	df	MS	F	P-value
Between Groups	7191.6	1	7191.6	4.99	0.0669
Within Groups	8653.4	6	1442.2		
Total	15845.0	7			

Table 36 ANOVA of mean temperature for the upper heat tile by unit (degrees Celsius).

SUMMARY

Groups	Count	Sum	Average	Variance
Burn upper	4	261.6	65.4	74.9
Thin and Burn upper	4	351.4	87.8	742.1

ANOVA

Source of Variation	SS	df	MS	F	P-value
Between Groups	1009.3	1	1009.3	2.47	0.1670
Within Groups	2451.3	6	408.5		
Total	3460.7	7			

The same relationship was found when the maximum temperature achieved in each unit was tested using a single factor ANOVA. The lower tile in the thin and burn had a significantly higher maximum temperature, while the upper showed no difference (Tables 38 and 39).

Table 37 ANOVA of maximum temperature for the lower heat tile by unit (degrees Celsius).

SUMMARY

Groups	Count	Sum	Average	Variance
Burn max	4	1067.7	266.9	2636.3
Thin & Burn max	4	2290	572.5	37229.9

ANOVA

Source of Variation	SS	df	MS	F	P-value
Between Groups	186728.4	1	186728.4	9.37	0.0226
Within Groups	119598.8	6	19933.1		
Total	306327.2	7			

Table 38 ANOVA of maximum temperature for the upper heat tile by unit (degrees Celsius).

SUMMARY

Groups	Count	Sum	Average	Variance
Burn max	4	727.8	181.9	3919.7
Thin & Burn max	4	985	246.3	7804.8

ANOVA

Source of Variation	SS	df	MS	F	P-value
Between Groups	8270.4	1	8270.4	1.41	0.2798
Within Groups	35173.4	6	5862.2		
Total	43443.8	7			

Finally, a relationship between mean temperature at the lower tile and the amount of downed woody fuel (fuels including 1-hour fuels and up) and total fuels that included all downed woody fuels, litter, and duff were investigated. Fuels loading data was gathered and provided by Rodger Ottmar from the PNW Research Station out of Seattle. A significant relationship was found between the mean temperature and the downed woody fuels only (Table 40). Average woody fuel loadings were 13.1 and 25.2 tons per acre post-prescribed fire for the burn and thin and burn treatments.

Table 39 Simple linear regression for fuels greater than 1-hr (1/4" or greater) versus lower heat tile

Regression Statistics	
Multiple R	0.92
R Square	0.85
Adjusted R Square	0.83
Standard Error	19.85
Observations	8

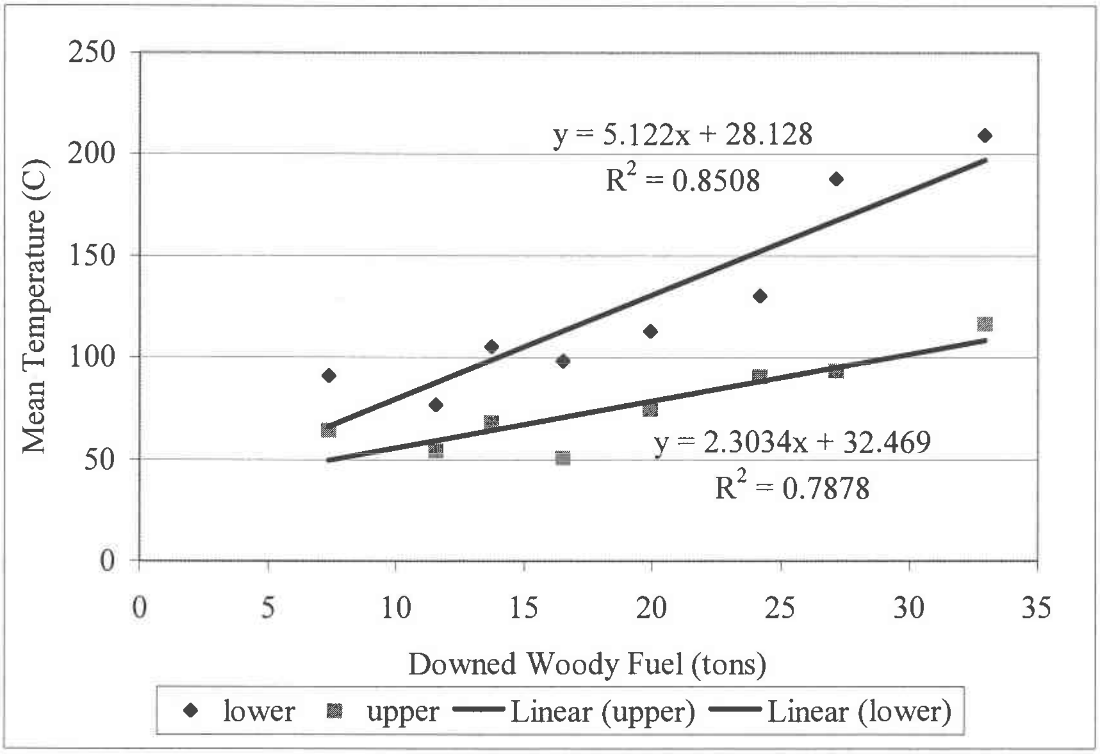
ANOVA

	df	SS	MS	F	Sig. F
Regression	1	13481.0	13481.0	34.2	0.0011
Residual	6	2364.01	394.0		
Total	7	15845.0			

	Coefficients	Standard. Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	28.13	18.19	1.54	0.1718	-16.39	72.65
Tons Woody Fuel	5.12	0.87	5.84	0.0011	2.97	7.2

As downed woody fuels increased, the mean temperature increased by 5.1 degrees Celsius for every ton of downed woody fuels (Figure 24). A significant relationship was also found at the upper heat tile with an increase of 2.3 degrees for every ton of downed woody fuel.

Figure 24 Simple regression for fuels great than 1-hr (1/4" or greater) for both upper and lower heat tile.



Model Simulations for Sensitivity Analysis

The following figures (Figures 25 to 48) are the output produced from the model simulation. Only one variable was changed at a time so compounding effects would not be present. It is also important to note that stand conditions not being altered are averages from the actual study units. The high, medium, and low efficiency harvester-forwarder pairs are shown for both net revenue per ton and acre in all figures. The following explains the iterative runs and describes what variable was modified and by what magnitude. In addition, the equations for each efficiency level are reported along with their standard error and R^2 value.

The first group of model simulations involved increasing the amount of total wood being harvested (ton/acre) either as live trees, standing dead trees, or downed wood. In each scenario, the proportion of sawlogs, pulpwood, and cull was held constant at the conditions of the field study and only the volume of the live, dead, and downed material increased as each was independently investigated.

For the live wood simulation, Table 41 and Figures 25 and 26 show the effect on net revenue as tons per acre of increases from 10 to 50 tons while all other levels remained the same. Due to the composition of live wood, 66% sawlogs, 22% pulpwood, and 12% cull, and the higher value of sawlogs, a positive response was observed in net revenue.

From Figure 25, a logarithmic trend was observed and the equations derived as the quantity of live wood removed begins to dominate the equation (Table 41). Net revenue per ton increases and then begins to flatten out, approaching the price received to harvest only live wood. Net revenue per acre increased for all levels of efficiency, linearly, by differing magnitudes and the derived equations are shown in Table 41.

Table 40 Predictive equations for net revenue per ton and acre as live wood removal level (tons) is changed for the high, medium, and low efficiency systems.

Net Revenue per Ton ($)		
Efficiency Level[1]	Predictive Equation {Standard Error, Respectively)	$\%R^2$
High[2]	12.26 * Log(tons live wood) – 26.27 {0.67, 1.98}	94.7
Medium[3]	11.51 * Log(tons live wood) – 28.40 {0.66, 1.93}	94.4
Low[4]	12.15 * Log(tons live wood) – 34.13 {0.69, 2.01}	94.5
Net Revenue per Acre ($)		
Efficiency Level[1]	Predictive Equation {Standard Error, Respectively)	$\%R^2$
High[2]	20.40 * (tons live wood) – 144.51 {.069, 1.60}	100
Medium[3]	15.38 * (tons live wood) – 142.60 {.043, 1.01}	100
Low[4]	12.41 * (tons live wood) – 159.57 {.054, 1.27}	99.9

[1]Efficiency level is the classification for equipment combinations based on production rates and cost.
[2]High efficiency combination, Rottne harvester and Timbco forwarder.
[3]Medium efficiency combination, John Deere harvester and Rottne SMV Rapid forwarder.
[4]Low efficiency combination, Caterpillar harvester and Rottne Rapid.

Figure 25 Effect of live wood removed on net revenue per ton.

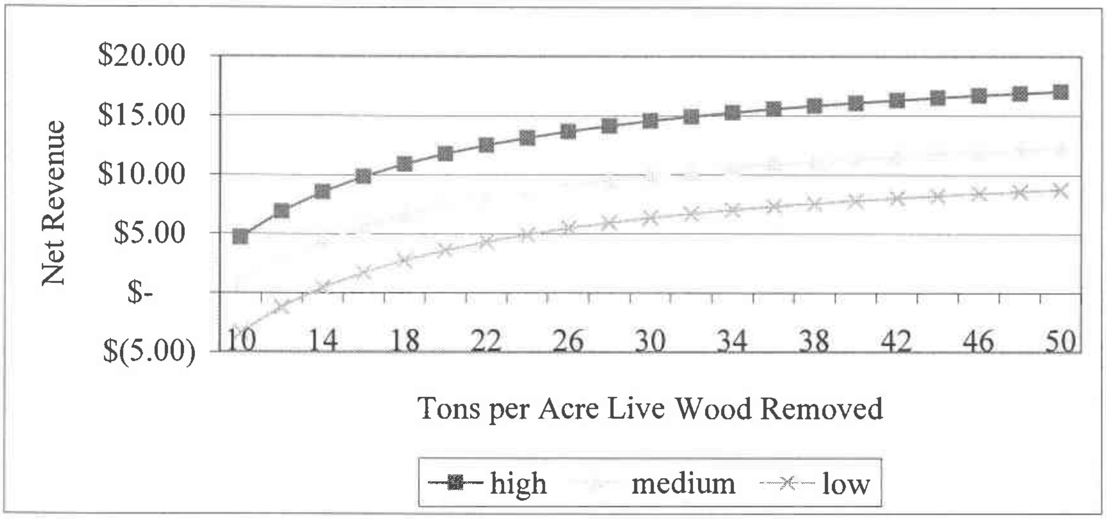
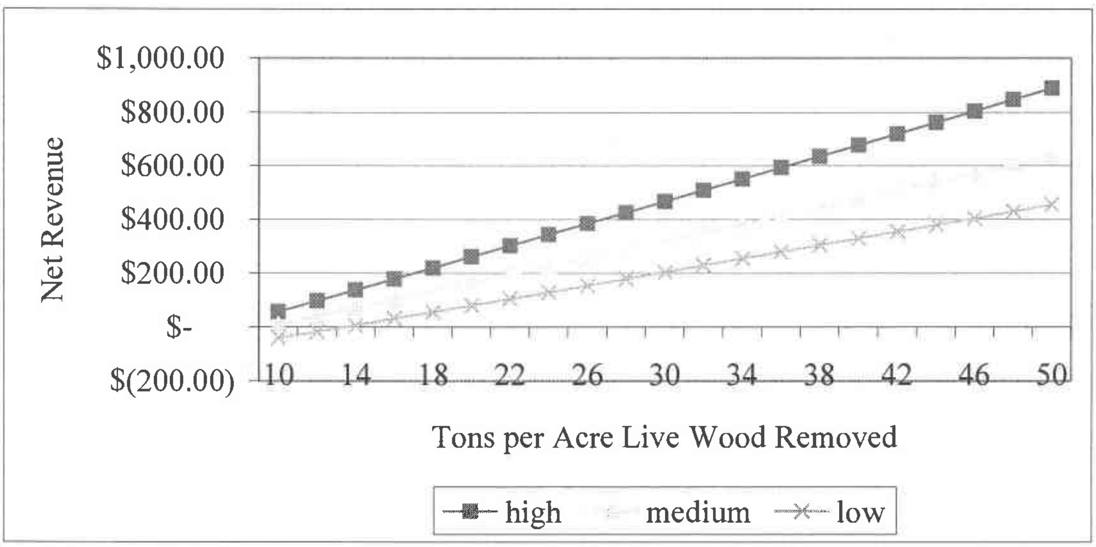


Figure 26 Effect of live wood removed on net revenue per acre.



For the standing dead simulation, Table 42 and Figures 27 and 28 show the effect of material being removed as it ranges from 0 to 40 tons per acre. Standing dead removed consisted of 30% sawlogs, 50% pulpwood, and 20% cull. The higher portion of pulpwood (compared to live trees) in the standing dead material caused a loss in net revenue per ton for all levels of efficiency while only the high efficiency system increased in net revenue per acre as the value per ton of material remove did not fall below its operating cost. The equations in Table 42 were derived and a logarithmic relationship was found for net revenue per ton and a linear relationship was observed for net revenue per acre (Table 42).

Table 41 Predictive equations for net revenue per ton and acre as standing dead removal level (tons) is changed for the high, medium, and low efficiency systems.

Efficiency Level[1]	Net Revenue per Ton ($) Predictive Equation {Standard Error, Respectively)	%R^2
High[2]	-1.83 * Log(tons standing dead) + 16.30 {0.07, 0.20}	97.2
Medium[3]	-2.06 * Log(tons standing dead) + 11.96 {0.08, 0.24}	96.9
Low[4]	-2.34 * Log(tons standing dead) + 9.64 {0.09, 0.27}	96.9

Efficiency Level[1]	Net Revenue per Acre ($) Predictive Equation {Standard Error, Respectively)	%R^2
High[2]	5.21 * (tons standing dead) + 425.98 {0.03, 0.69}	99.9
Medium[3]	-0.56 * (tons standing dead) + 303.95 {0.02, 0.43}	98.1
Low[4]	-5.57 * (tons standing dead) + 200.55 {0.02, 0.55}	100

[1]Efficiency level is the classification for equipment combinations based on production rates and cost.
[2]High efficiency combination, Rottne harvester and Timbco forwarder.
[3]Medium efficiency combination, John Deere harvester and Rottne SMV Rapid forwarder.
[4]Low efficiency combination, Caterpillar harvester and Rottne Rapid.

Figure 27 Effect of standing dead removed on net revenue per ton.

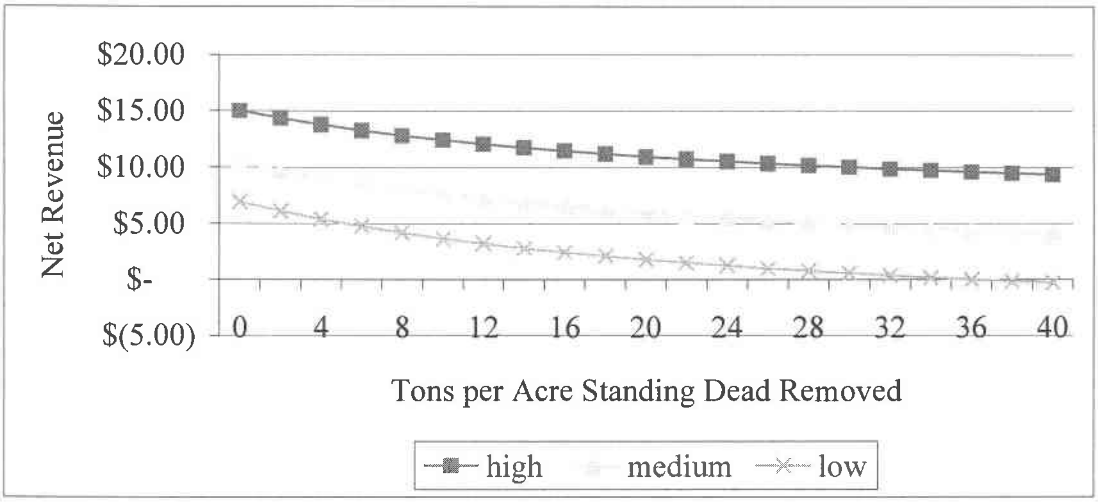
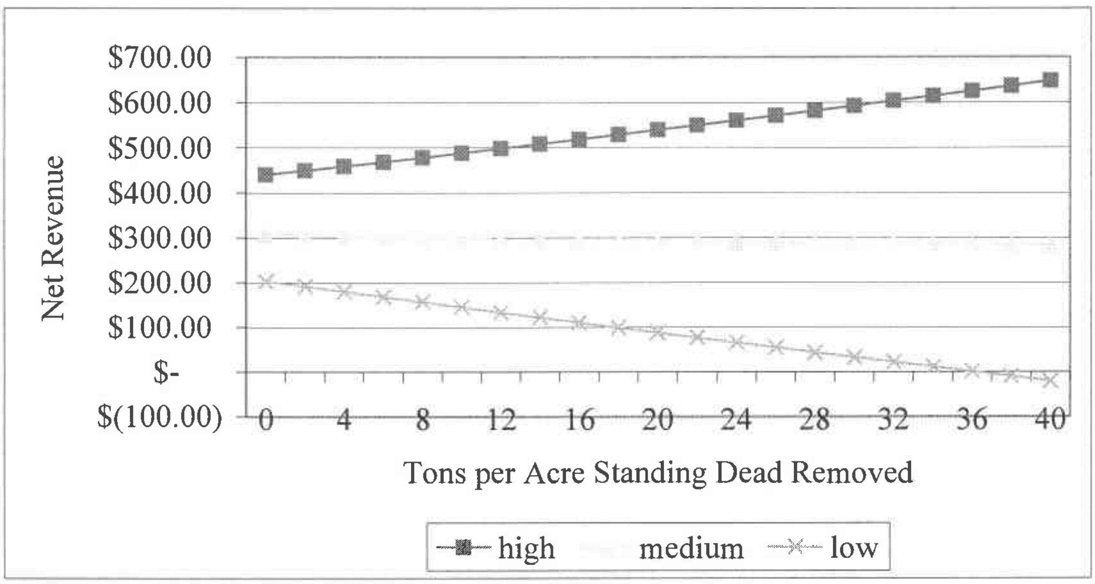


Figure 28 Effect of standing dead removed on net revenue per acre.



For the downed wood simulation, Table 43 and Figures 29 and 30 show the effect of downed wood removal as it ranges from 0 to 40 tons per acre. Downed wood removed consisted of 5% sawlogs, 65% pulpwood, and 30% cull. The low percentage of saw logs and high portion of pulpwood and cull (compared to live and standing dead trees) makes this material limited in value and it causes the net revenue per ton and acre to go down in all cases.

Figure 29 shows the logarithmic trend derived and Figure 30 the linear trend. Table 43 shows the predictive equation for each level of efficiency with standard error estimates and R^2.

Table 42 Predictive equations for net revenue per ton and acre as downed wood removal level (tons) is changed for the high, medium, and low efficiency systems.

	Net Revenue per Ton ($)	
Efficiency Level[1]	Predictive Equation {Standard Error, Respectively)	%R^2
High[2]	-3.88 * Log(tons downed wood) + 17.48 {0.16, 0.47}	97.0
Medium[3]	-4.17 * Log(tons downed wood) + 13.15 {0.17, 0.52}	96.8
Low[4]	-4.76 * Log(tons downed wood) + 10.01 {0.20, 0.59}	96.8

	Net Revenue per Acre ($)	
Efficiency Level[1]	Predictive Equation {Standard Error, Respectively)	%R^2
High[2]	-6.59 * (tons downed wood) + 445.53 {0.04, 0.90}	99.9
Medium[3]	-12.77 * (tons downed wood) + 304.54 {0.03, 0.56}	100
Low[4]	-19.53 * (tons downed wood) + 192.77 {0.03, 0.71}	100

[1]Efficiency level is the classification for equipment combinations based on production rates and cost.
[2]High efficiency combination, Rottne harvester and Timbco forwarder.
[3]Medium efficiency combination, John Deere harvester and Rottne SMV Rapid forwarder.
[4]Low efficiency combination, Caterpillar harvester and Rottne Rapid.

Figure 29 Effect of downed wood removed on net revenue per ton.

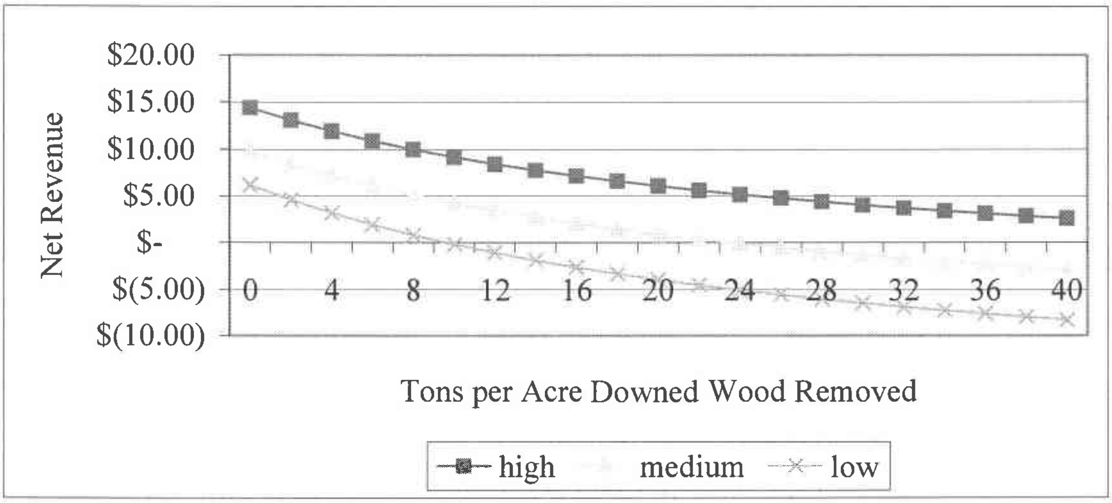
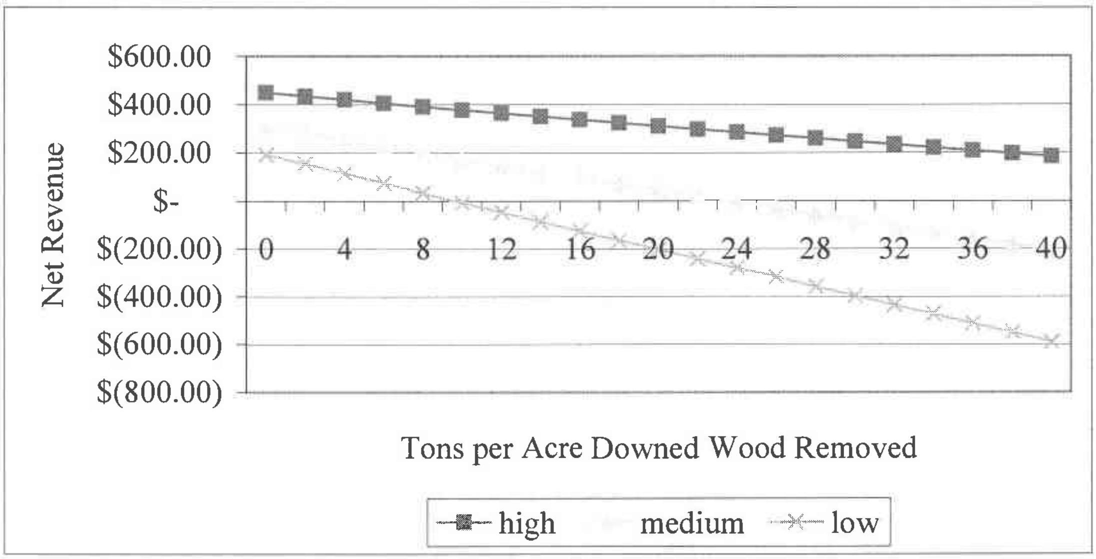


Figure 30 Effect of downed wood removed on net revenue per acre.



The next model simulation varied the mean diameter of all material removed (live, standing dead, and downed material). Stand conditions (other than diameter used) were the values determined from the field study data (as such there was a large portion of live trees in the simulation run). For the change in diameter simulation, Table 44 and Figures 31 and 32 illustrate how diameter at the base of the tree or large end of the downed material affects the over all production rates with values ranging from 6 to 26 inches (Dia. for diameter at base or large end in inches). As diameter increased, volume per stem increased and harvest production increases to a point then decreases. A polynomial relationship was derived from the simulation showing that overall production increases to a point where volume per stem is negatively impacted by the increased processing times with large diameter trees and downed material (Table 44).

Table 43 Predictive equations for net revenue per ton and acre as diameter at the base of the stump or large end is changed for the high, medium, and low efficiency systems.

Net Revenue per Ton ($)		
Efficiency Level[1]	Predictive Equation[5] {Standard Error, Respectively)	%R^2
High[2]	$-0.047 * (Dia.)^2 + 1.20 * (Dia.) + 8.55$ {0.001, 0.05, 0.33}	99.3
Medium[3]	$-0.051 * (Dia.)^2 + 1.31 * (Dia.) + 3.48$ {0.001, 0.05, 0.36}	99.4
Low[4]	$-0.067 * (Dia.)^2 + 1.79 * (Dia.) – 2.43$ {0.002, 0.07, 0.53}	98.9

Net Revenue per Acre ($)		
Efficiency Level[1]	Predictive Equation {Standard Error, Respectively)	%R^2
High[2]	$-1.47 * (Dia.)^2 + 37.46 * (Dia.) + 266.9$ {0.04, 1.40, 10.30}	99.4
Medium[3]	$-1.59 * (Dia.)^2 + 40.74 * (Dia.) + 108.64$ {0.05, 1.51, 11.09}	99.4
Low[4]	$-2.08 * (Dia.)^2 + 55.79 * (Dia.) – 75.81$ {0.07, 2.24, 16.40}	98.9

[1]Efficiency level is the classification for equipment combinations based on production rates and cost.
[2]High efficiency combination, Rottne harvester and Timbco forwarder.
[3]Medium efficiency combination, John Deere harvester and Rottne SMV Rapid forwarder.
[4]Low efficiency combination, Caterpillar harvester and Rottne Rapid.
[5]Dia. is the diameter at base of the or large end in inches.

Figure 31 Effect of diameter for saw wood on net revenue per ton.

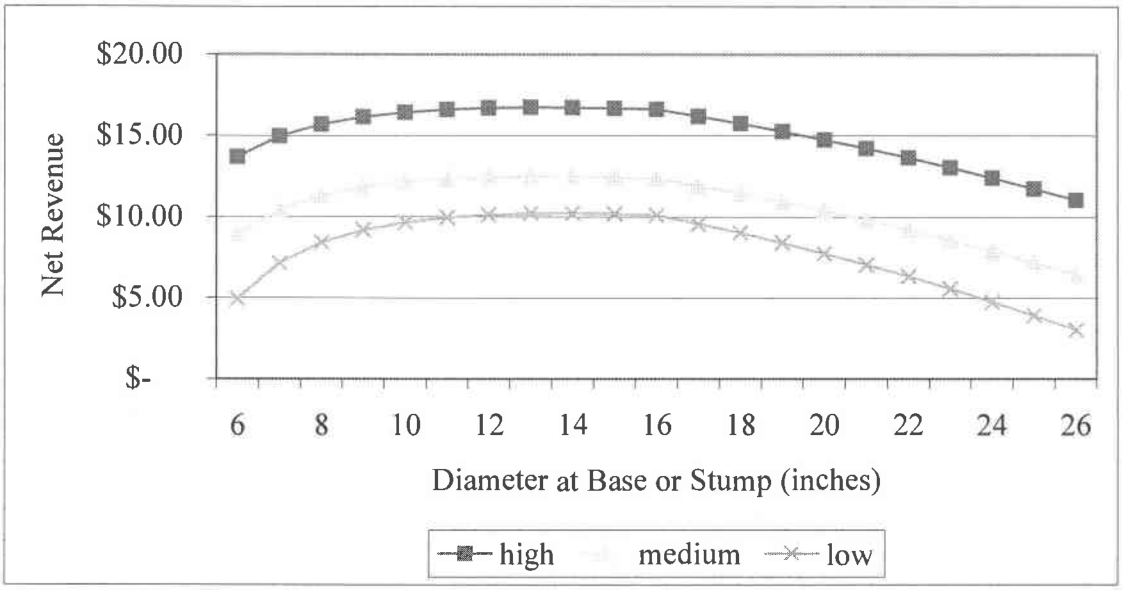
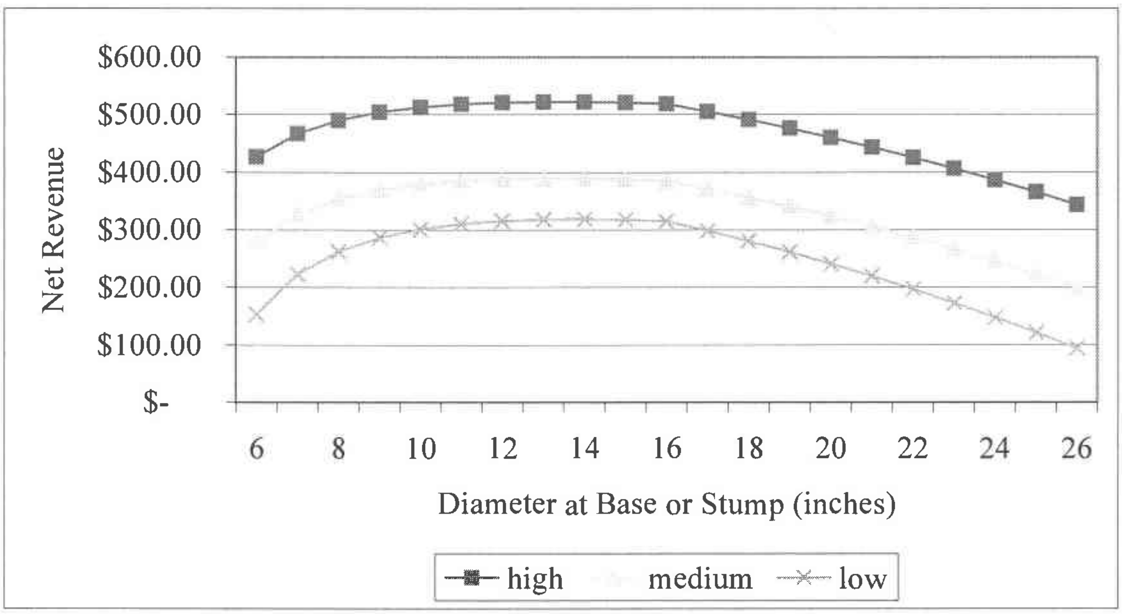


Figure 32 Effect of diameter for saw wood on net revenue per acre.



Model simulations then varied the percentage of sawlogs to pulpwood (from 100% to 0%) for different levels of total material removed per acre. In this case equal portions of the material removed were distributed evenly over the live, standing dead, and downed classes (no cull or deduction was used). All other variables in this simulation were those derived from the studies field data.

From the simulations for percent sawlogs to pulpwood ratio, Tables 45-47 and Figures 33 to 38 show a series that compares the ratio to total wood removal levels of 20, 40 and 60 tons per acre. As shown in the derived equation and previous simulations, the higher valued sawlogs are what provides the positive return on net revenue (Tables 45-47). As sawlog composition increases the high and medium efficiency systems increase with a similar magnitude while the low efficiency system does not respond as favorably to the increase (Tables 45-47). Further, increasing the amount of total material removed per acre moves the breakeven point (net revenue is zero) over to the right of the graph meaning a lower percentage of sawlogs is needed to break even (Figures 33 to 38).

Table 44 Predictive equations for net revenue per ton and acre as percent sawlogs to pulpwood changes for 20 tons removed for the high, medium, and low efficiency systems.

Net Revenue per Ton ($)		
Efficiency Level[1]	Predictive Equation {Standard Error, Respectively)	%R^2
High[2]	0.35 * (percent sawlogs) – 9.97 {0.0002, 0.009}	100
Medium[3]	0.36 * (percent sawlogs) – 13.97 {0.0001, 0.006}	100
Low[4]	0.44 * (percent sawlogs) – 26.04 {0.0001, 0.007}	100

Net Revenue per Acre ($)		
Efficiency Level[1]	Predictive Equation {Standard Error, Respectively)	%R^2
High[2]	7.15 * (percent sawlogs) – 199.40 {0.003, 0.18}	100
Medium[3]	7.20 * (percent sawlogs) – 279.49 {0.002, 0.12}	100
Low[4]	8.87 * (percent sawlogs) – 520.82 {0.002, 0.15}	100

[1]Efficiency level is the classification for equipment combinations based on production rates and cost.
[2]High efficiency combination, Rottne harvester and Timbco forwarder.
[3]Medium efficiency combination, John Deere harvester and Rottne SMV Rapid forwarder.
[4]Low efficiency combination, Caterpillar harvester and Rottne Rapid.

Table 45 Predictive equations for net revenue per ton and acre as percent sawlogs to pulpwood changes for 40 tons removed for the high, medium, and low efficiency systems.

	Net Revenue per Ton ($)	
Efficiency Level[1]	Predictive Equation {Standard Error, Respectively)	%R^2
High[2]	0.35 * (percent sawlogs) – 5.47 {0.0001, 0.007}	100
Medium[3]	0.36 * (percent sawlogs) – 10.09 {0.0007, 0.004}	100
Low[4]	0.44 * (percent sawlogs) – 21.90 {0.0009, 0.005}	100
	Net Revenue per Acre ($)	
Efficiency Level[1]	Predictive Equation {Standard Error, Respectively)	%R^2
High[2]	14.14 * (percent sawlogs) – 219.45 {0.004, 0.26}	100
Medium[3]	14.26* (percent sawlogs) – 403.65 {0.003, 0.16}	100
Low[4]	17.59 * (percent sawlogs) – 875.89 {0.004, 0.21}	100

[1]Efficiency level is the classification for equipment combinations based on production rates and cost.
[2]High efficiency combination, Rottne harvester and Timbco forwarder.
[3]Medium efficiency combination, John Deere harvester and Rottne SMV Rapid forwarder.
[4]Low efficiency combination, Caterpillar harvester and Rottne Rapid.

Table 46 Predictive equations for net revenue per ton and acre as percent sawlogs to pulpwood changes for 60 tons removed for the high, medium, and low efficiency systems.

	Net Revenue per Ton ($)	
Efficiency Level[1]	Predictive Equation {Standard Error, Respectively)	%R^2
High[2]	0.35 * (percent sawlogs) – 3.82 {0.0001, 0.005}	100
Medium[3]	0.36 * (percent sawlogs) – 8.69 {0.0001, 0.003}	100
Low[4]	0.44 * (percent sawlogs) – 20.38 {0.0001, 0.004}	100

	Net Revenue per Acre ($)	
Efficiency Level[1]	Predictive Equation {Standard Error, Respectively)	%R^2
High[2]	21.10 * (percent sawlogs) – 228.92 {0.005, 0.32}	100
Medium[3]	22.05 * (percent sawlogs) – 521.17 {0.003, 0.20}	100
Low[4]	26.29 * (percent sawlogs) – 1,222.61 {0.004, 0.25}	100

[1]Efficiency level is the classification for equipment combinations based on production rates and cost.
[2]High efficiency combination, Rottne harvester and Timbco forwarder.
[3]Medium efficiency combination, John Deere harvester and Rottne SMV Rapid forwarder.
[4]Low efficiency combination, Caterpillar harvester and Rottne Rapid.

Figure 33 Effect of percent sawlog composition at 20 tons per acre removed on net revenue per ton.

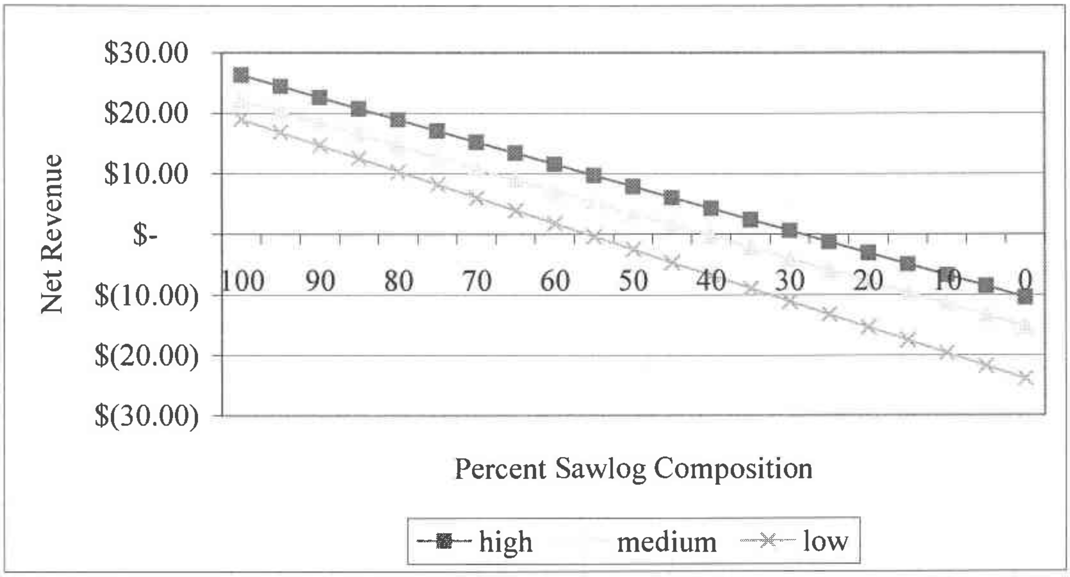


Figure 34 Effect of percent sawlog composition at 20 tons per acre removed on net revenue per acre.

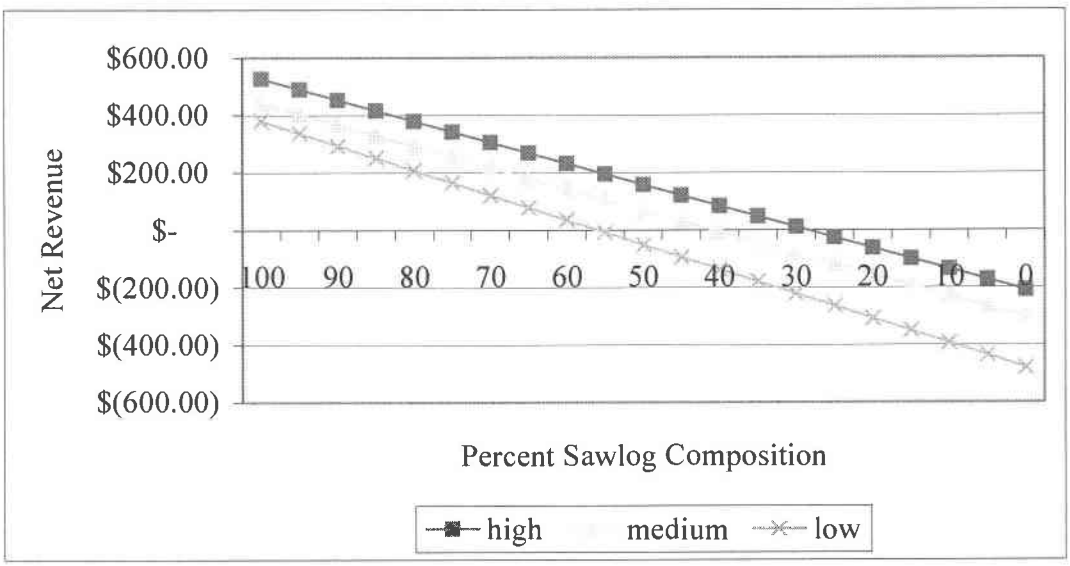


Figure 35 Effect of percent sawlog composition at 40 tons per acre removed on net revenue per ton.

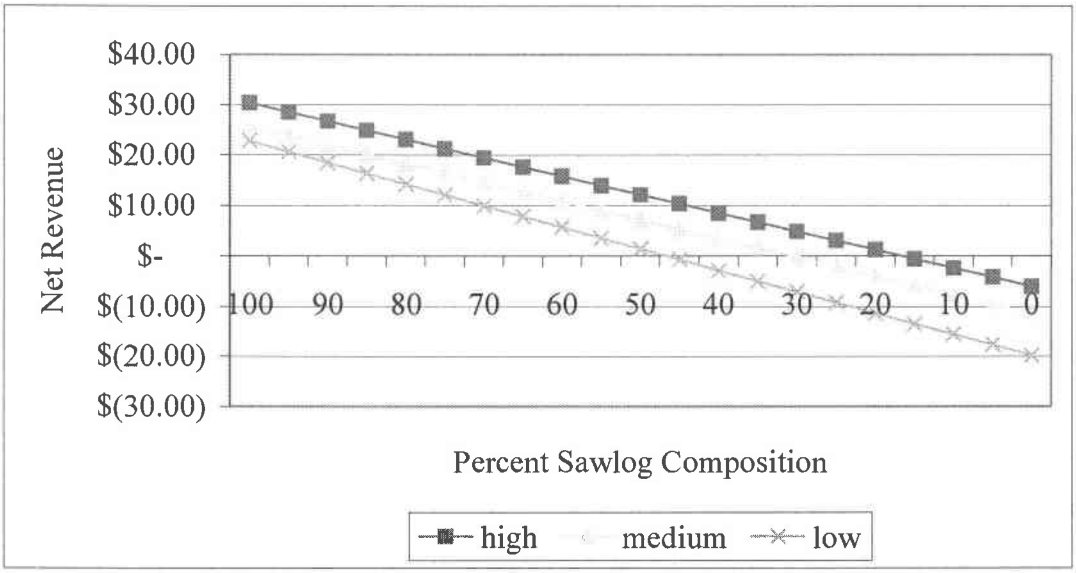


Figure 36 Effect of percent sawlog composition at 40 tons per acre removed on net revenue per acre.

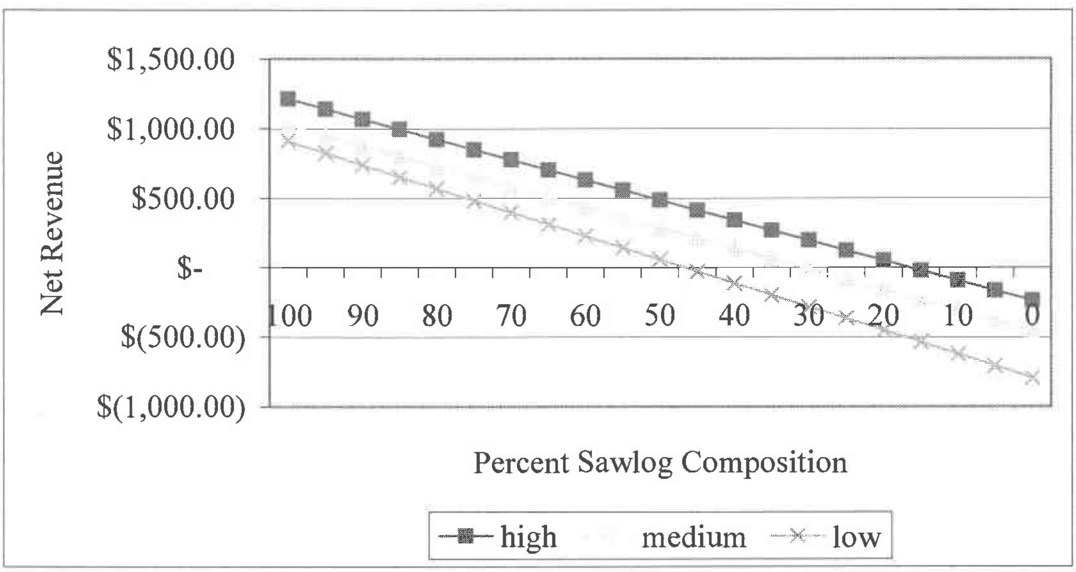


Figure 37 Effect of percent sawlog composition at 60 tons per acre removed on net revenue per ton.

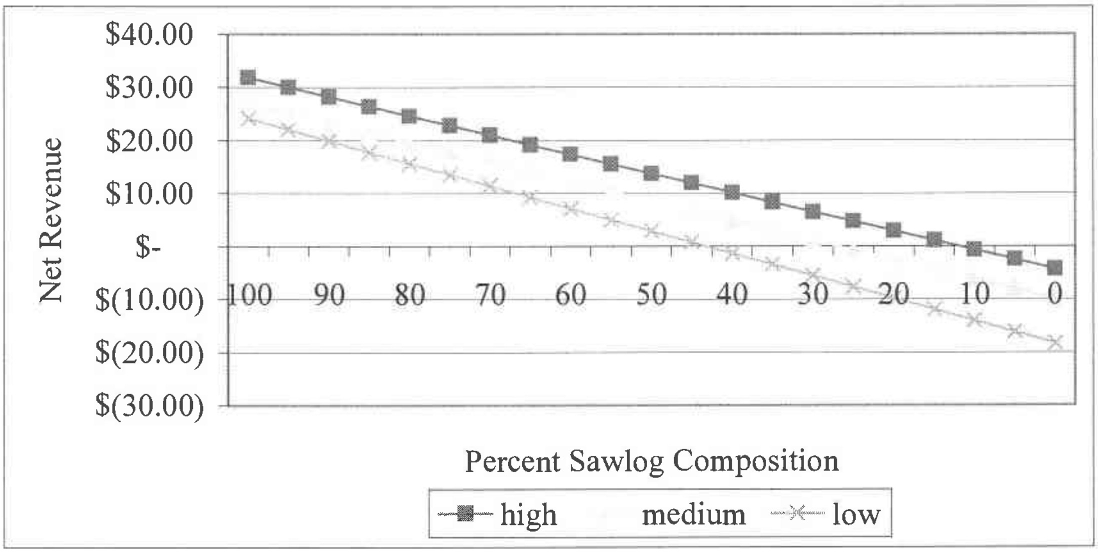
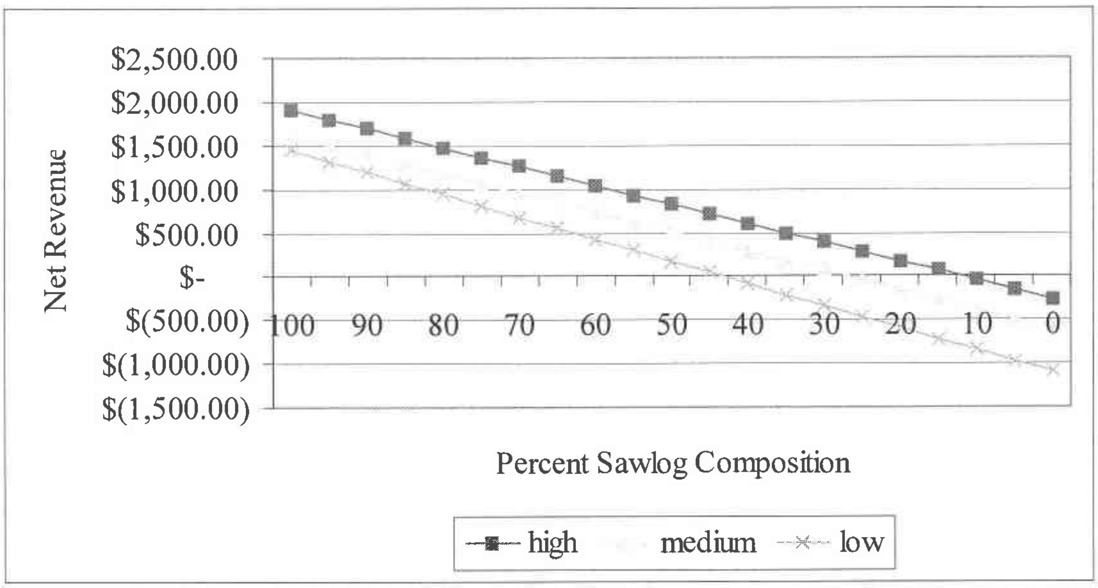


Figure 38Effect of percent sawlog composition at 60 tons per acre removed on net revenue per acre.



The next simulation run investigated the effect of percent utilization rate (%UR) for harvesting machinery on net revenue. Each efficiency level was varied from 100% (no delays) to 40% (60% down time and delays). In this case both the harvester and forwarder in each efficiency level was given the same %UR. All other variables remained constant and were left at the field study values. Table 48 and Figures 39 and 40 show the derived polynomial relationship. As machinery becomes less productive, the fixed costs begin to become more pronounced in the overall cost equation causing an increasing reduction in net revenue.

Table 47 Predictive equations for net revenue per ton and acre as percent utilization (%UR) is changed for the high, medium, and low efficiency systems.

Net Revenue per Ton ($)		
Efficiency Level[1]	Predictive Equation {Standard Error, Respectively)	$\%R^2$
High[2]	$-0.003 * (\%UR)^2 + 0.68 * (\%UR) - 18.03$ {0.002, 0.03, 0.90}	99.7
Medium[3]	$-0.005 * (\%UR)^2 + 1.01 * (\%UR) - 39.68$ {0.003, 0.04, 1.33}	99.7
Low[4]	$-0.006 * (\%UR)^2 + 1.20 * (\%UR) - 52.05$ {0.003, 0.05, 1.58}	99.7

Net Revenue per Acre ($)		
Efficiency Level[1]	Predictive Equation {Standard Error, Respectively)	$\%R^2$
High[2]	$-0.103 * (\%UR)^2 + 12.23 * (\%UR) - 563.00$ {0.006, 0.84, 28.07}	99.7
Medium[3]	$-.153 * (\%UR)^2 + 31.48 * (\%UR) - 1{,}237.78$ {0.009, 1.24, 41.61}	99.7
Low[4]	$-1.81 * (\%UR)^2 + 1.47 * (\%UR) – 1{,}623.73$ {0.01, 1.47, 49.35}	99.7

[1]Efficiency level is the classification for equipment combinations based on production rates and cost.
[2]High efficiency combination, Rottne harvester and Timbco forwarder.
[3]Medium efficiency combination, John Deere harvester and Rottne SMV Rapid forwarder.
[4]Low efficiency combination, Caterpillar harvester and Rottne Rapid.

Figure 39 Effect of changing utilization rate from 100% to 40% for all pairs on net revenue per ton.

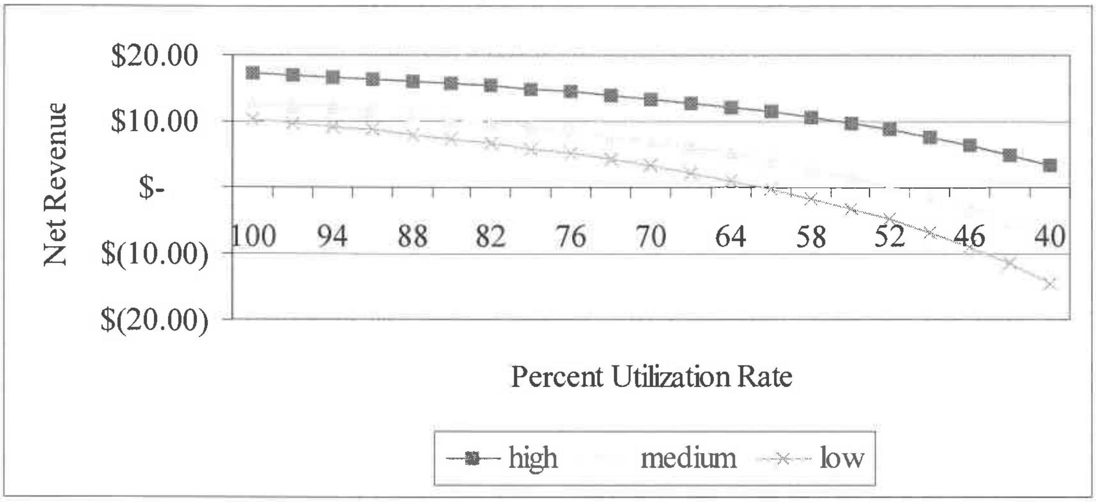
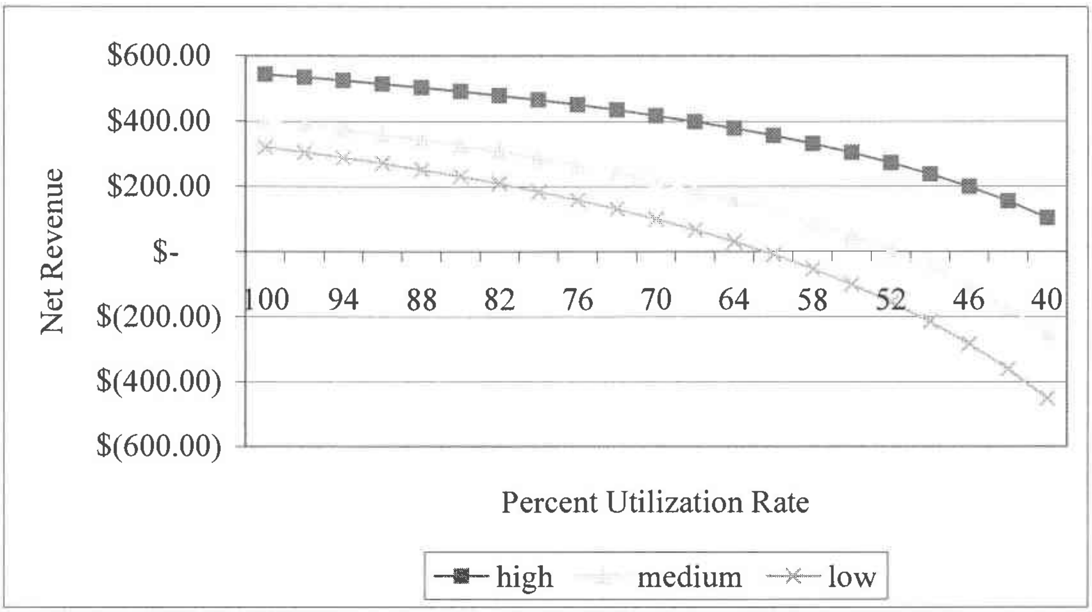


Figure 40 Effect of changing utilization rate from 100% to 40% for all pairs on net revenue per acre.



Two simulation runs were then conducted on market price. Figures 41 and 42 show the response to a change in the market price for sawlogs from $40 to $60 per ton and Figures 42 and 43 shows the response to a change in the market price for pulpwood from $10 to $30 per ton. The increase in net revenue is a response to the mix of material being removed and to the price for sawlogs and pulpwood. The mix represented the actual amounts removed from the study sites (66% of live trees, 30% standing dead, and 6% downed were scaled as sawlogs). Due to the similarity of the slopes within each graph, only the intercepts (at a market value of zero for the derived regression equations) are reported below along with the common slope. Intercept values are the value at a market price of zero for sawlogs and pulpwood and the slope is the response of net revenue to a change in market price of one dollar. The regression equation had a $\%R^2$ with a perfect fit at 100% and the standard errors were < 0.005.

Change in market price of sawlogs and its effect on net revenue per ton (Figure 41) produced a positive slope of 0.63 and intercepts of –$20.49, –$25.12, and –$28.72 per ton for the high, medium, and low efficiency systems, respectively. For net revenue per acre (Figure 42) the slope was 19.78 and intercepts were –$639.21, –$783.27, and –$895.88 per acre for the high, medium, and low efficiency systems, respectively.

Change in market price for the pulpwood and its effect on net revenue per ton (Figure 43) produced a positive slope of 0.24 with intercepts at $9.58, $4.96, and $1.35 per ton for the high, medium, and low efficiency systems, respectively. For net revenue per acre (Figure 44) the slope was 7.48 with intercepts of $298.82, $154.75, and $42.14 per acre for the high, medium, and low efficiency systems, respectively.

To determine the break-even point where net revenue is zero, the negative intercept is divided by the slope. A sawlog price of $32.5, $39.9, and $45.58 per ton is needed in order for the high, medium, and low efficiency systems (respectively) to breakeven at a net revenue of zero dollars per ton and acre. Looking at the market value of pulpwood, with positive intercepts derived for all of the efficiency systems pulpwood value did not cause net revenue to drop below zero. The above calculations were, again, using actual field study data.

Figure 41 Effect of changing market price of saw logs from $40/ton to $60/ ton on net revenue per ton.

Figure 42 Effect of changing market price of saw logs from $40/ton to $60/ ton on net revenue per acre.

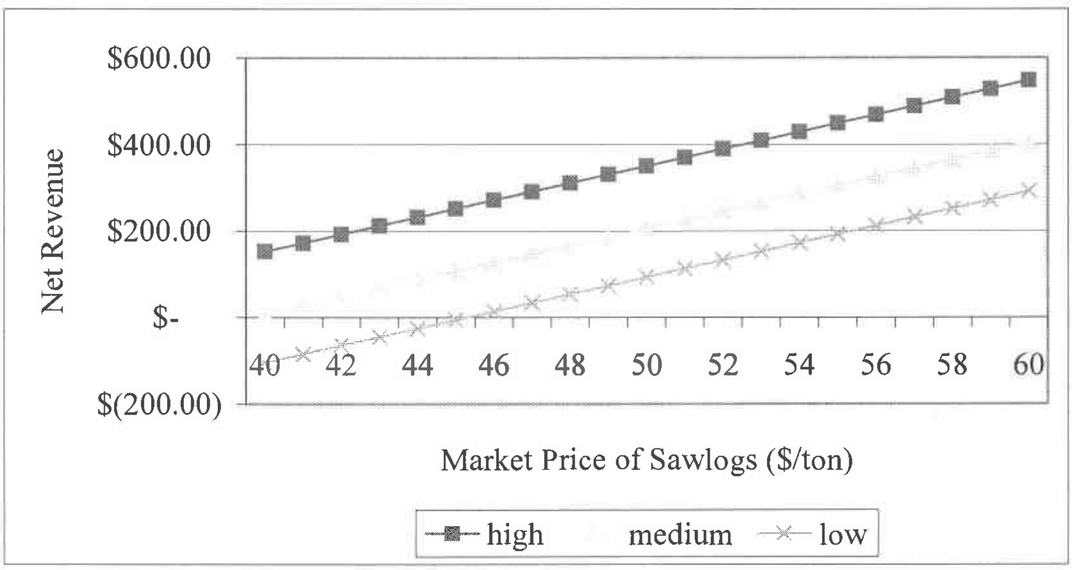


Figure 43 Effect of changing the market price of pulpwood $10/ton to $30/ton on net revenue per ton.

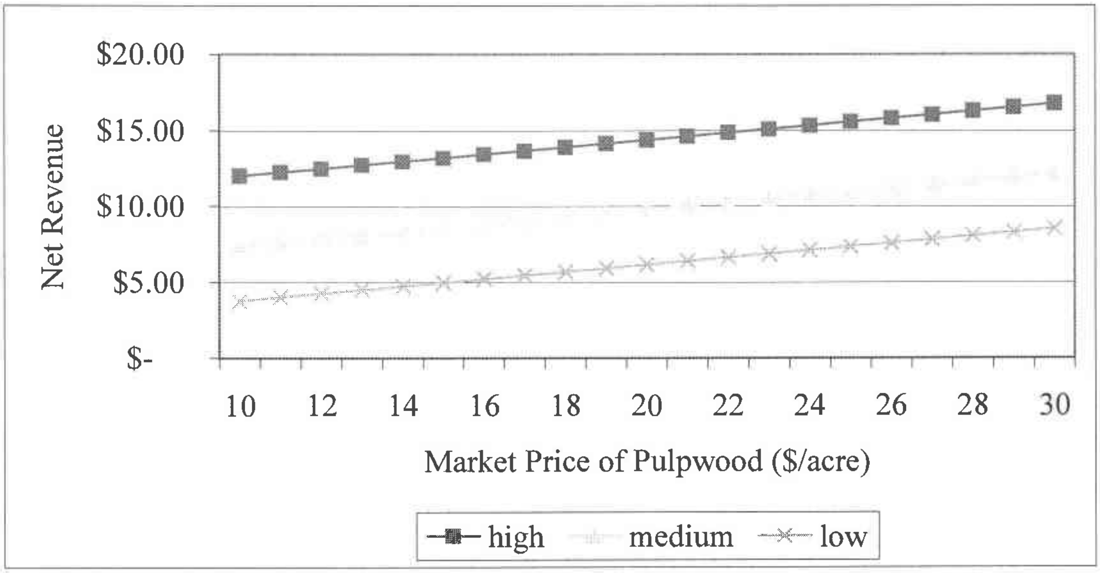
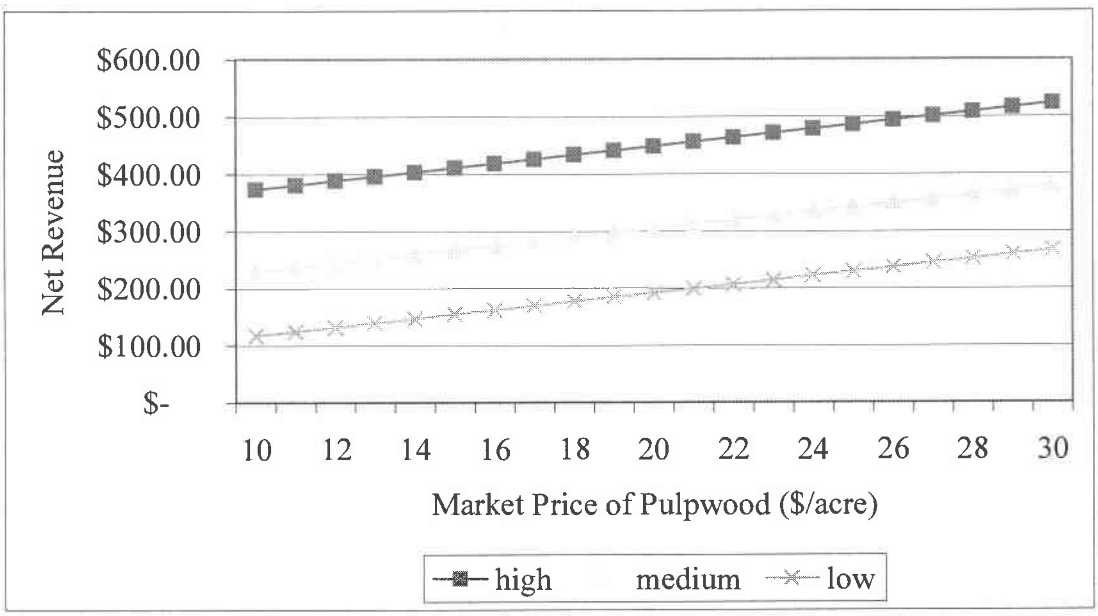


Figure 44 Effect of changing the market price of pulpwood $10/ton to $30/ton on net revenue per acre.



The primary tree species on and around the study area were ponderosa pine and Douglas-fir. To see what affect this composition has on net revenue, a simulation was run. The derived costs in Figures 45 and 46 show the response to a change in tree species composition ranging from 100% Douglas-fir to 100% ponderosa pine. There is little effect of species composition on net revenue; only increasing slightly as percent ponderosa pine composition increases. Net revenue increased by $0.60 per ton over the range of 0% to 100% ponderosa pine composition for the high efficiency and $0.90 for the low efficiency system. Net revenue per acre followed the same linear trend with a range of $19.18 to $29.76 per acre for the high and low level systems, respectively. This overall, limited, effect was due to similar market prices and the same mill destination.

Figure 45 Effect of changing species from 0% ponderosa pine to 100% Douglas-fir on net revenue per ton.

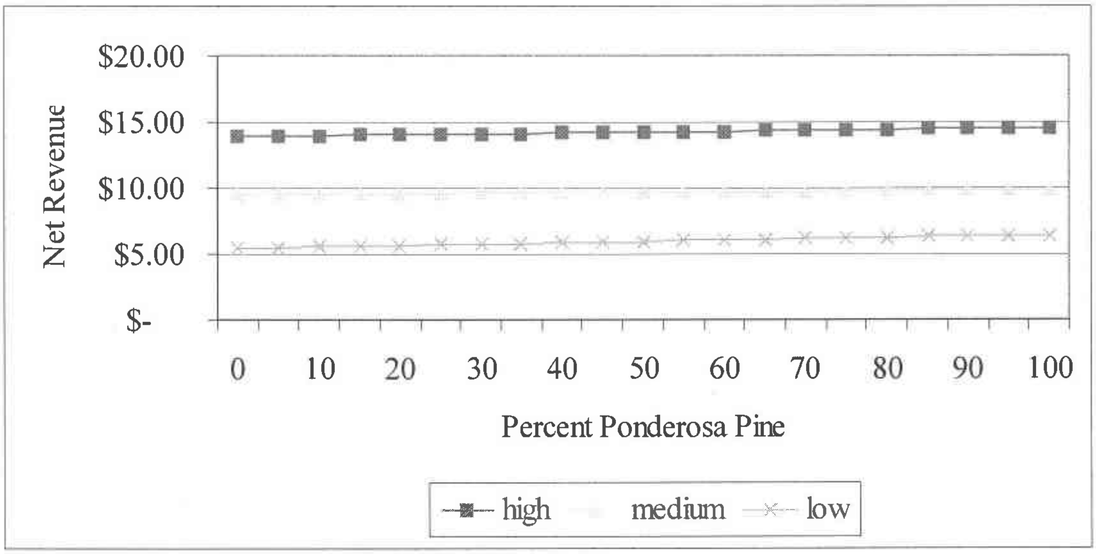
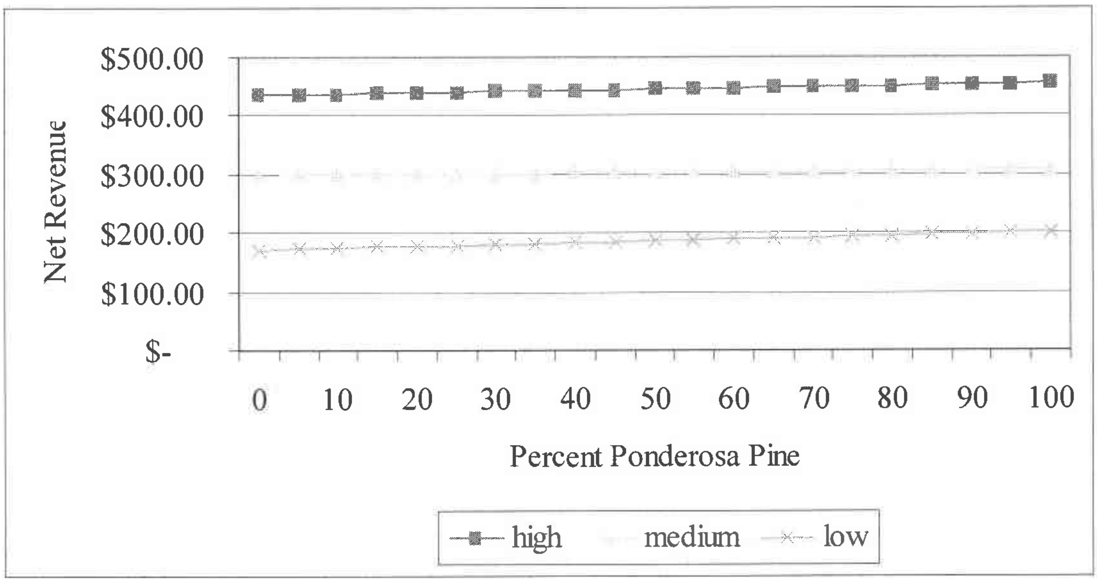


Figure 46 Effect of changing species from 0% ponderosa pine to 100% Douglas-fir on net revenue per acre.



Transport distance to the mill site often varies and the following simulation runs show how this variable impact the over all net revenue. In Figures 47 and 48 the effect of increasing the cost of transporting the logs to the mill in total cost per load is shown. Again, the slopes of the lines within each figure are the same and there is only a difference in the intercept. Standard errors were below 0.002 for all intercepts and below 0.00001 for both slopes. Net revenue per ton changes negatively with a slope of –0.046 for every additional one-dollar increase in hauling cost, and the intercepts for the high, medium, and low efficiency systems are 21.28, 16.66, and 13.05, respectively. The change in net revenue per acre comes at a rate of loss of $1.43 per acre for every additional dollar increase in hauling cost and intercepts of $663.66, $519.59, and $406.99 for the high, medium, and low efficiency systems, respectively.

Figure 47 Effect of change in hauling cost from $100 to $400 per load on net revenue per ton.

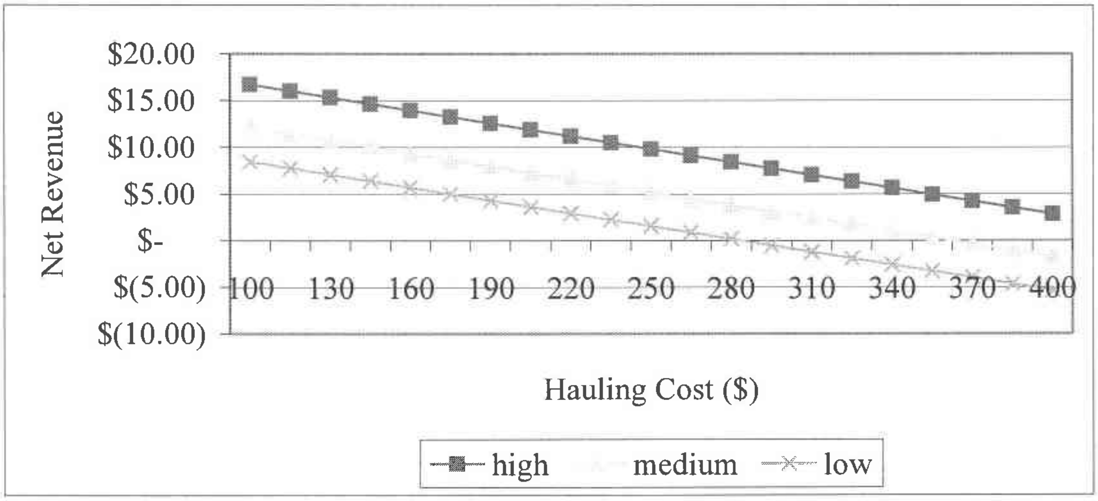
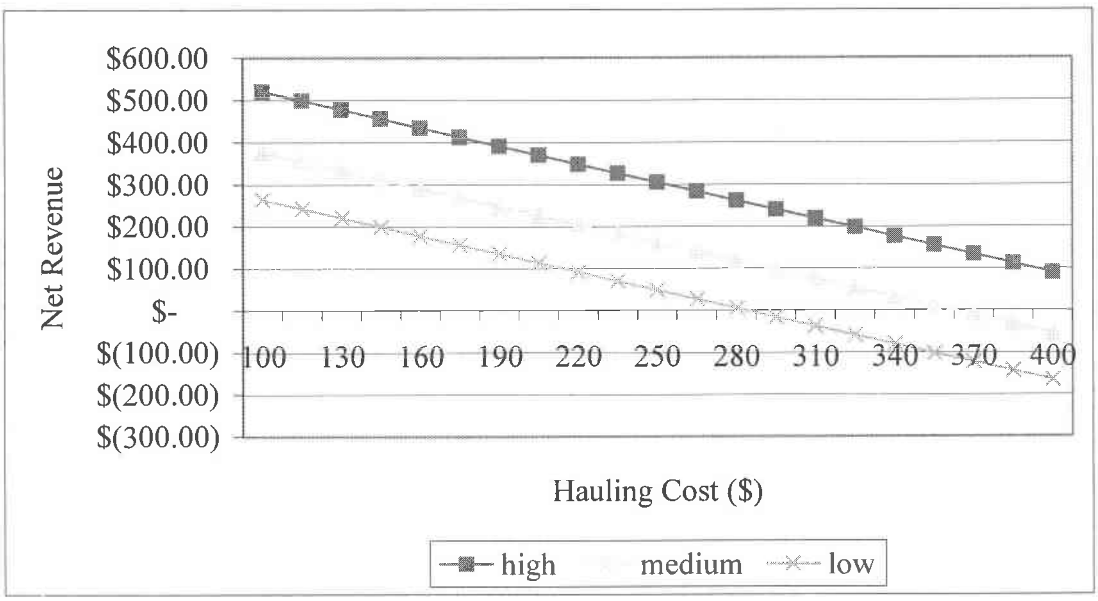


Figure 48 Effect of change in hauling cost from $100 to $400 per load on net revenue per acre.



Discussion

Harvester and Forwarder Performance

The three different harvesters produced significantly different production rates within the stand conditions observed. The Rottne and John Deere were purpose build machines, while the Caterpillar was retrofitted with a modified boom and equipped with a single-grip harvester head. The three forwarders also exhibited different performance capabilities. The larger Timbco out-performed both the Rottnes, which had similar production rates.

Harvester Processing and Travel Time

From the summary statistics in Table 15, the time element "process" was found to be significantly different between the single-grip harvesters. The Rottne felled, limbed, and bucked all types of material (live, stand dead, and downed) in an average time of 40.9 hundredth of a minute per piece (PMH). This was 28.6% and 71.4% faster than the John Deere and Caterpillar, respectively. While the utilization rate of the Rottne was 15% lower than the John Deere and Caterpillar, the Rottne still out-performed the other machines in a SMH comparison. One factor for this difference between machines was attributed to the harvester head design, the rapid feed rate and saw speed of the Rottne's EGS 600 (15.2 ft/sec) processing head as compared to the

Waratah HTH Warrior (13.2 ft/sec) and Keto 500 (11.8 ft/sec) on the John Deere and Caterpillar, respectively. While the Rottne had the fastest processing rate, it was only 3 hundredths of a minute faster (per tree) than the John Deere's Waratah processing head when compared on production per SMH rather than PMH. When comparing both of these machines to the Caterpillar's retrofitted Keto 500 processing head, the Cat was out-performed by almost a quarter of a minute per tree. Due to the limited ability of the retrofitted boom design to position the head for felling and subsequently process the tree into log lengths, on average, the Caterpillar was significantly less productive in processing trees on a SMH basis.

Move time was found to be a significant variable in predicting the harvesting time for individual stems (Tables 12, 13, and 14), but there were no significant differences between the three harvesters (Table 15). The Rottne was rubber-tired mounted and the John Deere and Caterpillar were track-mounted. It would be expected that the rubber-tired machine could achieve a higher travel speed between processing locations, and therefore take less time moving. However, due to the short distances moved between processing of trees, vehicle speed was equally matched. Machine maneuverability, associated with the time it took to achieve proper positioning for processing, played an important role. The track-mounts had better capabilities for positioning the machine although their travel speeds were notably slower. The lack of significance in the time element "move" between the three harvesters is attributed to the combination of short distances moved, travel speed, and maneuverability.

Processing of Material: Live, Standing Dead, and Downed Wood

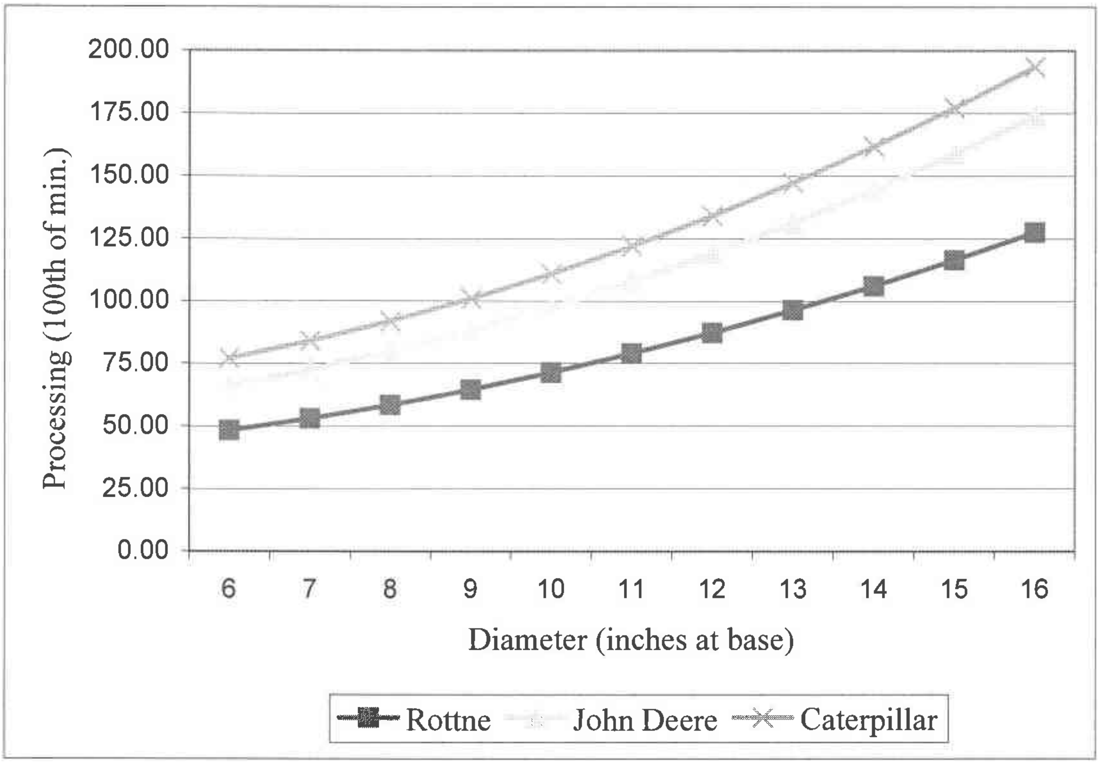
Using the predictive equations derived for each harvester, the processing of the three categories of material removed (live, standing dead, and downed) was found to be different between machines and within the harvester cycle times (PMH). For live material (the most common type removed), the Rottne's cycle time was higher by 36.5% and 57.9% than that of the John Deere and Caterpillar, respectively. For standing dead material, the Rottne processed material significantly faster than the John Deere and Caterpillar. However, the Caterpillar had a slightly faster processing speed than the John Deere by 3 hundredth of minute. Lastly, the merchantable, downed woody material removed from the forest floor was processed the fastest by the Rottne. The Rottne processed material at a rate of 34.2% and 178.0% faster than the John Deere and Caterpillar, respectively. Again, differences between the purpose built and retrofitted boom design were a contributing factor to the speed at which these machines processed material. Further, the Keto 500 harvester head has a limited capacity to pick-up downed material. The Caterpillar and Keto 500 head took longer to process downed wood than live and standing dead material (Table 14), by 3.9 and 29.4 hundredth of minute, respectively. A Caterpillar representative confirmed this limitation of the Keto 500 head, stating that its design does not allow for processing downed material as efficiently as the Rottne EGS 600 or Waratah HTH Warrior (Pers. Comm. William H. Rambo, Forestry Manager, Caterpillar Inc., Bellevue, WA, 2003).

Within an individual harvester's cycle time, on average, it took longer to process live trees followed by standing dead and then downed material. With the exception of the Caterpillar, live trees took nearly twice the time to process as downed material and processing times for standing dead fall between the two. Longer processing times could be attributed to the increased tree length and associated number of logs that were cut out of each live tree and the greater number of limbs (especially live limbs) on live trees. Further, discussion on this matter and associated limbing capability is covered in the differences in tree species.

Diameter of Material Removed

Diameter of material removed was found to be a significant variable for determining the processing time of an individual stem (as was found in related stuides). A transformation by taking the square of the diameter values was applied and found to be significant, while the diameter term alone or together with the $diameter^2$ term was not. All things being equal within the cycle time, the Rottne was affected the least by a change in diameter, followed by the John Deere and Caterpillar. Figure 49 shows the relationship between diameter and processing time for live ponderosa pine trees of varying diameters.

Figure 49 Harvester processing time for live ponderosa pine as diameter increases (hundredth of minutes).



Species of Material Removed

Ponderosa pine and Douglas-fir were the primary species removed from the harvest units. Species was a significant independent variable in the harvesters' predictive equation; Douglas-fir took slightly longer to process than the ponderosa pine. With an increased processing time of 4.8, 3.2, and 8.5 hundredth of a minute per tree (Rottne, John Deere, and Caterpillar, respectively), it took approximately an additional 10% in processing time for the Douglas-fir species.

With both species exhibiting similar height, diameter, and form, the limbs on the Douglas-fir did not 'pop' off as easily during the delimbing stage while the tree was being fed through the processing head and between the delimbing knives. One difference (as reported by the manufacture of the processing heads) was the force at which a tree could be fed through the head. The John Deere's Waratah head has a rated feeding force of 37.6 kN while the Rottne EGS 600 is rated at 33.7 kN and the Caterpillar's Keto 500 at 31.4 kN.

Forwarder Performance

The distance traveled and number of stops per cycle were significant variables in predicting the cycle time for all forwarders. In addition, there were performance differences between the three forwarders. The three machines had a different rated maximum-working load. The Timbco, Rottne SMV, and Rottne Rapid were rated at 16, 12, and 10 tons, respectively. All things being equal, it would be expected that the machine with the lowest max-working load would produce the highest number of loads per unit of time. That is, if the travel speed, distance traveled, and volumes per acre were the same, it would produce more loads per unit time at a lower weight or volume per load; however this was not the case. In the shift level study, the Timbco produced 0.24 more loads per PMH than the Rottne SMV and Rottne Rapid. Furthermore, the increase in the maximum-working payload and increased utilization rate only magnifies these productivity differences. As shown in Table 10, on average the forwarders were loaded to, or just above, their rated payload.

Average loads per SMH for the Timbco, Rottne SMV, and Rottne Rapid were 1.31, 1.03, and 0.99, respectively. With average skidding distances and volume per acre similar, no one reason for the difference in production could be determined. Three factors that are hypothesized to have created these differences are operator experience, machine power and stability, and harvest planning. The primary operator for the Rottne Rapid had less than one year of experience operating the machine and was being trained. The Rottne Rapid operator was in the middle of the learning curve and was probably not working the machine to its fullest potential. The other two operators had three years of experience in their respective machines.

Another consideration in forwarder performance was the power and stability of the machine. The Timbco was an eight-wheel machine with bogies in the front and rear, whereas the Rottnes were six-wheel with only bogies in the rear. The added advantage for negotiating obstacles and slopes could have aided in machine ability to move through the stand at great speeds and up the isolated steeper areas faster.

Finally, harvest planning and equipment selection for the different units and placement within units was observed to have favored the Timbco for areas with higher volumes of timber removed. With these areas occurring in isolated areas and at random, this was only observational and not possible to quantify. To further emphasize this pre-planning selection, the smaller forwarders were often placed in areas with higher residual densities due to their greater ability to maneuver through the stand. This observed condition appeared to contribute to the machines' reduced performance.

Burn Treatment Cost and Logistics

Total personnel hours were the driving force in the cost of the prescribed burn. While vehicles assigned to the different units and supplies varied, their overall effect on cost was not a significant factor (less than 10% of total cost). Due to the variation in pay rate and hours in overtime by the different prescribed fire crew members, standardizing the pay rate and hours worked was an appropriate process to complete for a better comparison of treatments. Comparing the actual cost to the standardized prescribed fire costs, the average treatment costs per acre were similar to each other. Without any alteration to the cost data, the actual prescribed fire cost incurred by the USDA-Forest Service was $61.2 per acre. Comparing the actual cost to the standardized cost with overtime ($60.1 per acre), a difference of $1.1 per acre or less than 2% was determined. Next, by eliminating an overtime pay rate from the standardized cost calculations, a lower dollar per acre treatment costs was determined ($50.50 per acre). The removal of this variability was necessary for determining any cost differences between treatments. The order in which the units were burned was conducted without any input from the researchers to emulate the actual protocol used by the USDA-Forest Service. As a result, a unit that was ignited towards the later part of the shift incurred more overtime than a unit ignited at the beginning of a shift. By eliminating all overtime, the costs could be better compared. The use of a profit and risk or overtime factor for conducting a prescribed fire could include a 25% increase for potential overtime. This factor accounts for a 50% chance that a prescribed burn would occur during an overtime shift. Furthermore, cost standardization was needed because some personnel were on a salaried rate rather than an hourly rate and did not incur any overtime. It is better for the actual organization conducting the burn to include these costs as they vary between crews and organizations.

With respect to cost, the pre-treatment effect of burning or thinning and burn was found not to be significant at the 95% confidence level. External factors, such as temperature, relative humidity, wind, and topography, added high levels of variability to the rate at which fire spreads and the control efforts of the prescribed fire crew. The burn only treatment, at an average cost of $48.75 per acre, was just over eight dollars less than the thin and burn treatment at $56.80 per acre. The variability within the cost data for the thin and burn treatment was over two times that of the burn only. The presence and arrangement of activities fuels (residual slash left from the harvesting operation) in these units could have been another factor that introduced variability.

Thin and burn units 6B and 11 & 12 were the most costly at $84.24 and $87.34 per acre, respectively. These two units were small and had an increased level of personnel conducting the burn with respect to the other burn and thin and burn units. When the costs were broken down into units that were either smaller or larger than the average size, six units were smaller and two units were larger. In this analysis, the effect of area size was found to be insignificant at the 95% confidence level, but significant at the 90% confidence level. The lower cost to burn the larger areas could be attributed to the increased size absorbing the fixed costs and procedures that typically occur on a prescribed burn. Mobilization and organization at the site occurred in every case. A briefing of the unit, crew assignments, and logistics followed this. On the average, travel and planning time made up 31% of the total time spent during the burn operation.

However, when size and treatment type were both introduced into the model a significant relationship was found. While this relationship is encouraging to report, it needs to be taken with some caution. Due to the great variability reported in Table 27 the use of this model to predict future prescribed burn operations is limited. While it is significant, it should only be used to look at the trends that occurred in the study units and not applied to operations elsewhere. With the inclusion of a more robust data set through future research projects in fire economics, the analysis would provide a better understanding of treatment and acreage cost effects. A model with lower variability and a more robust data set could provide the predictions for future operations within the study region.

Effect of Thinning on Fire Intensity and Resource Implications

As shown by the heat tile data, thin and burn treatments burned hotter than burn only treatments. The presence of the activity fuels, as well as the spatial arrangement of these fuels, is discussed in this section. Other resource implications are discussed and future management suggestions are made based on the prescribed fire response.

Effects of Activity Fuels on Fire Line Intensity

On the average, it was found that the downed woody fuels were higher in the thin and burn units than in other treatments prior to the prescribed fire (see Figure 50 for photo of fire activity). With nearly double the fuels, higher fire line intensity would be expected. This was noted at both the lower and upper heat tiles when individual plots were compared. However, due to the small sample size (n=8) and high variability when comparing the means of each unit, the fire intensity was not found to be statistically significant between treatments. Only the lower tiles had a statistically significant difference if a rejection/acceptance level of 0.1 is used. Regardless of how one looks at fire intensity, all things being equal, with lower levels of downed woody material, the fire line intensity will not be as hot in most prescribed conditions.

It will not be known for some time what the overall effects of the prescribed fire are on the residual stand for both the burn and thin and burn treatments. However, one could hypothesize that mortality levels in the burn only units will be lower than the thin and burn units, and probably not sufficient to meet the desired post-treatment stocking levels. Further, unwanted mortality in the larger dominant and co-dominant trees will be higher in stands that were thinned prior to burning as they achieved a higher temperature threshold. Tree mortality and stand growth will be monitored by the La Grande PNW Station over the next several years and will be reported in the future as part of the Fire, Fire Surrogate study.

Figure 50 Prescribed fire treatment burning through and area with activity fuel concentrations.

Several factors typically associated with the activity fuels created by the cut-to-length harvesting system contributed to an increase in fire line intensity. First is the size and shape of the fuels. Smaller fuels require less heat to remove fuel moisture and raise a small fuel particle to ignition temperature (Pyne et al. 1996). Most of the limbs and tops would be considered to be in the smaller fuel size class that drive and increase fire line intensity (10 to 100-hour fuels or 1-3" in diameter). Since burning was conducted two years post-harvest, the activity fuels had substantial time to dry, but not enough time had elapsed for the needles and smaller activities fuels to break down. Second are fuel concentrations. Fuels that are piled will burn hotter than separated fuels due to the increase in radiant heat transfer (Pyne et al. 1996). A single-grip harvester typically works in strips spaced 40 to 50 feet apart. As the machine moves through the stand, it typically processes multiple stems from a stationary location, limbing and topping the trees in front of the machines' path. As a result, fuels concentrate in clumpy strips where the machine travels. The third factor, also associated with fuel concentration, is the compactness level of the activity fuels. Compactness can be thought of as the spacing between fuel particles (Pyne et al. 1996). Loosely compacted fuels burn faster and hotter due to an increased availability of oxygen and radiant energy transfer (Pyne et al. 1996). While the harvester and forwarder traveled over some of the material, the number of passes on an individual trail was limited to only one pass by the harvester and typically two by the forwarder. Furthermore, due to the elastic nature of the green limbs and tops, the woody material would spring back after being crushed down by the machines, leaving fuels elevated slightly from the surface (see Figure 51 for photo of fuels located in forwarder trails). Finally, the activity fuels left by the harvesters were arranged both horizontally and vertically, creating good conditions for both fire spread and intensity. Fuels that are arranged horizontally promote the fire spread rate or potential to spread, while the vertically-positioned fuels increase the fire line intensity (Pyne et al. 1996).

Figure 51 Looking up a forwarder trail post-logging at the fuel concentrations and distribution of activity fuels.

Resource Implications

While the increased fire line intensity due to activity fuels should not discourage the use of a cut-to-length system with prescribed fire, it does require a few pre-planning considerations that should be addressed. The first operational planning consideration is to avoid processing material around the bases of residual trees, snags, and large downed woody material that is to be retained. By keeping the concentrations of fuels away from the base of trees, the heat pulse traveling up the bole and into the live crown can be reduced, therefore reducing the risk of excessive tree scorch and lower bole damage.

Next would be to reduce the length of continuous strips of fuel concentrations left by the harvester, especially ones that run across slopes. On gentle ground, it is general practice to run the machines with the slope rather than perpendicular to the slope. As the prescribed fire lighting crews, who typically ignite from the top of a burn unit down, encounter a continuous line of fuel concentrations, a large flaming front can result. This in turn is fueled by creating in stand weather conditions that promote higher fire line intensities (typically increased wind velocity). Strips of fuel concentrations that run with the slope would allow the lighting crew to better control the fire intensity. A final suggestion would be to burn the unit closer to its time of harvest before the activity fuels dry out too much. By allowing the larger activity fuels to retain a higher moisture content at the time of harvest, the reaction intensity of the fuels would be reduced.

Another implication related to the mechanized harvesting is stand damage. While damaging of the lower bole or crown of a residual tree can promote problems on its own (i.e., spread of disease), it also interacts with prescribed fire. Most of the trees (especially the ponderosa pine) that had a portion of the bark removed on the lower bole of the tree produced a substantial amount of pitch and resin accumulation around the wound. This material was commonly ignited by the prescribed fire and burned for many hours and smoldered for days (see Figure 52 for photo of flaming tree wound). While collecting the data following the burn, trees with wounds were observed to be smoldering around the wounds and some were still flaming. This heat concentration into the bole of the tree caused a larger cavity to be produced and magnified the impact of the wound to the tree. These wounds and tree damage will be monitored with mortality and growth response over time and reported on in the future by other researchers.

Figure 52 Ignition of the resin and pitch from a tree wound along a skid trail.

Matrix for Different Harvester and Forwarder Combinations

As was shown in Table 24, the amount of time each piece of equipment worked in a treatment unit introduced some variability into the cost analysis. This resulted from using the actual costs and production rates for specific equipment combinations and time spent by these pieces of equipment in individual treatment units for the economic analysis. This variability, however, produced an excellent comparison of different cut-to-length equipment used in forest restoration and fuels reduction. With distinctly different harvesters and forwarders working throughout the study, a 3 by 3 matrix was created to show the range of costs and revenues that can occur in this stand type and residual removal level.

From the data collected and costs analysis, a total harvesting cost and net revenue matrix were produced which allows comparison of the different combinations of harvesters and forwarders used in the study (Tables 49 and 50). With respect to the study conducted by the California Department of Forestry (2001), The costs derived below were similar.

Table 48 Total harvesting cost matrix for the three harvesters and three forwarders in dollars per acre.

	Total Cost $/acre	Harvester Type Rottne	John Deere	Cat
Forwarder Type	Timbco	$788.83	$795.51	$876.72
	Rottne SMV	$926.23	$932.90	$1014.12
	Rottne Rapid	$957.62	$964.29	$1,045.51

Table 49 Total net revenue matrix for three harvesters and three forwarders in dollars per acre.

	Net Revenue Cost $/acre	Harvester Type Rottne	John Deere	Cat
Forwarder Type	Timbco	$448.45	$441.78	$360.56
	Rottne SMV	$311.05	$304.38	$233.17
	Rottne Rapid	$279.66	$272.99	$191.77

From this comparison, the ranges for total potential cost and net revenue for a specific machine combination are expressed for the average stand conditions used in the study. The basic concept of this matrix leads to the model that was constructed to compare the harvest systems based on the ranking of High, Medium, and Low (Table 10).

Effect of Stand and Operational Conditions on Economics of Treatments

While Tables 49 and 50 provide a useful reference to costs and revenues for mechanically treating the stands, more importantly it is important to understand which variables affect cost and revenue and by what magnitude. To further expand this, what combinations of equipment, treatment, and stand conditions are best utilized to accomplish the primary objective of fuels reduction and forest restoration while looking for the most economically feasible option? The model runs presented in Figures 25 to 48 provide an understanding of how stand and operational conditions affect the feasibility of a given treatment.

The goal was first to look at the primary factors that affect the harvesting operation. In the sensitivity analysis, average stand conditions were used as a baseline with only one variable changing at a time. In this manner, the overall impact on the system as a whole could be determined.

<u>Live Wood Removal</u>

In Figures 25 and 26 and Table 41, live wood removal was increased from 10 to 50 tons per acre. Due to the higher sawlog component and value associated with the live material, the response for increasing the quantity removed increases the net revenue. In Figure 24, the curve for revenue per ton begins to flatten out as fixed costs are absorbed. From Table 41 the equations for the three levels of efficiency can be used to predict the rate of change for the net revenue and the intercept at zero tons live removal. Net revenue per ton increased logarithmically by approximately the same magnitude for the three levels of harvest system efficiency. The medium and low efficiency systems net revenue increased for each additional ton of live wood removed by $15.38 and $12.41 per acre this is equivalent to 75% and 60% that of the high efficiency system (which was increasing at $20.40 for every ton of live wood removal), respectively. The value adding ability of live wood removal makes it an important consideration when designing an economically feasible or efficient operation. Three to four live trees were needed to provide 1 ton of wood removal. This gives a net revenue value per tree improvement of between $5.1 to $6.8 per acre. Slightly lowering the residual stocking level could provide an economical incentive to conduct operations that are netting a small loss or it could provide additional money to conduct other activities associated with the fuel reduction effort or forest restoration (i.e., prescribed fire or treatment of activity fuels). Similar notes were made by Brown (1995) and Doyle (1997), but were not quantified to the level of this study.

Standing Dead Removal

The response to increasing the level of standing dead removal was mixed. Brown (1995) found the primarily driving force to be the current market price of pulpwood, where as this study would a significant effect due to machine performance as well. As the level of standing dead is increased from 0 to 40 tons per acre, the revenue per ton decreases. Standing dead material is made up of a larger portion of pulpwood and cull when compared to live material and, while it is faster to process than live material, it still comes at a reduced net value. In terms of revenue per acre removal, the standing dead material incurred a cost for the low efficiency system of -$5.57 for every additional ton removed. In contrast, the high efficiency system gained revenue at a rate of +$5.21 per additional ton per acre removed. The medium efficiency system was almost net revenue neutral dropping to -$0.56 a ton per acre for each ton removed. With removal of standing dead material coming at both a net gain and loss, depending on harvesting equipment efficiency, it is important to understand how the equipment used in future harvests interacts with this material.

Downed Wood Removal

Removal of downed woody material had a significant negative economic impact on all equipment combinations. While similar studies have found advantages to using cut-to-length systems to be advantageous in small timber, all levels of harvesting efficiency lost revenue as tons of downed wood per acre increased from 0 to 40 tons. Limited value was received for this material due to the high proportion of pulpwood and cull in the downed wood, limited value was received for the delivered product. The high efficiency system lost $6.59 for every ton of downed wood removed per acre and the low efficiency system lost $19.53 for every ton (Table 43). The gap between the high and low systems was intensified by the limited ability of the

Caterpillar's Keto 500 head to process downed wood and the higher speed at which the Rottne could process the material (Pers. Comm. William H. Rambo, Forestry Manager, Caterpillar Inc., Bellevue, WA, 2003). Given average stand conditions, the net revenue breakeven point for tons of downed wood removed was 97.6, 23.9, and 9.9 tons removal per acre for the high, medium, and low efficiency systems, respectively. While revenue was being reduced (on the average) given the cost of transporting logs to the mill, it was still more economical to deliver the material than to remove it and then leave it on site. This will be discussed further in the section on change in transportation costs.

Diameter of Saw Wood

The average diameter at the stump was varied from 6 to 26 inches (Figures 31 and 32). Revenues increased from the 6-inch size class, then leveled off between 10 and 16 inches before falling again. As wood size increased, the processing time for an individual stem increased, as did the materials volume. Eventually the time to process increases at a faster rate than individual stem volmes increases and the cost effectiveness of using a cut-to-length system becomes less efficient. While some harvesting heads are designed for larger stems, the size of these trees reduces the speed at which the machine can limb and buck the logs. The average diameter of material removed on the study sites was 7.1 inches at the stump which is substantially less than 16 inches. These systems could be expected to perform well in stands of larger sized material but would see reduced revenues if the average diameter decreased. This conclusion and significant association is documented in other studies (Holtzscher and Landford 1996, Huyler and LeDoux 1996, Kellogg and Bettinger, 1994, and Makkonen 1991).

Percent Sawlogs versus Pulpwood at 20, 40, 60 Tons Removed per Acre

Figures 33 through 38 looked at the range of material removed per acre and investigated the breakeven point with respect to the mix of sawlogs and pulpwood. As more volume was removed the lower the percentage of sawlogs was required to have an operation that broke even (Tables 45 to 47). For the high efficiency system, the breakeven point for the 20, 40, and 60 tons per acre was 28%, 16%, and 11% sawlogs, respectively. For the low efficiency system, the breakeven point for the 20, 40, and 60-ton level was 58%, 50%, and 47%, respectively. The primary reasons for the shift in sawlog requirements were due to the increased value of sawlogs versus pulpwood and the fixed costs being applied over a larger volume of wood. For the high efficiency system, every additional percentage of pulpwood composition resulted in a reduction of $7.15, $14.14, and $21.10 per acre against the total revenue of $515.6, $883.11, and $1,406.39 per acre for 100% sawlog removal if 20, 40, and 60 tons were removed, respectively. The trend follows approximately the same pattern for the medium efficiency system except with a lower overall net revenue at a given percent sawlog composition. Net revenue for the low efficiency system was 25% less than (that of the high and medium systems) for every additional ton removed per acre. Again, while this was noted in Brown 1995, modeling efforts did not incorporate the level of robustness when compared to this study. In addition, it was found that the low efficiency system was also affected more by its reduced ability to process the pulpwood material.

Change in Utilization Rate

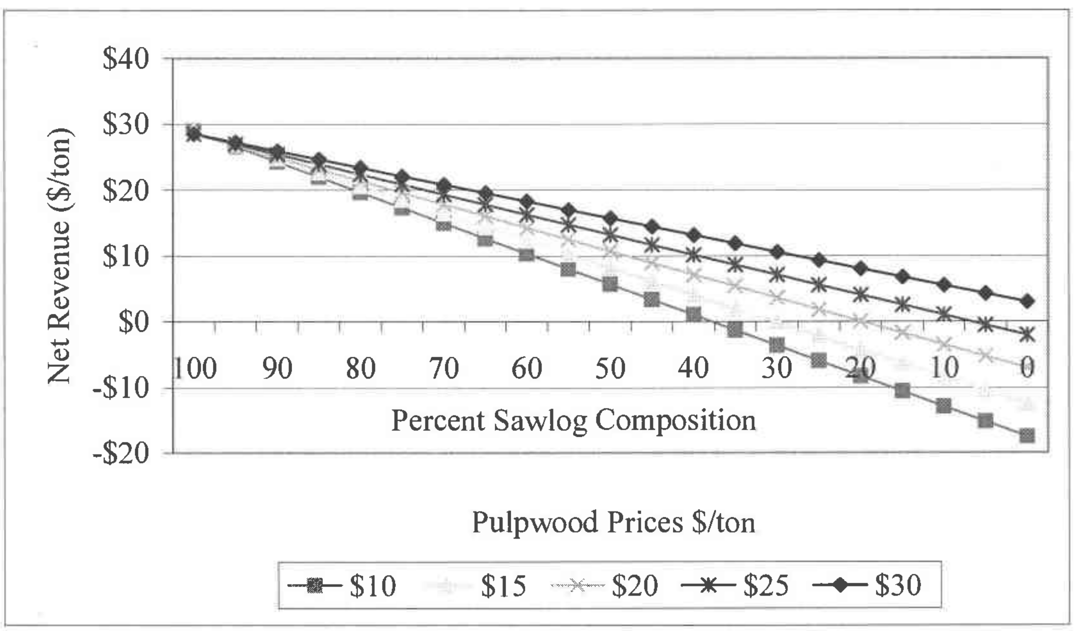
Change in the machine utilization rate affects how productive the equipment is and reflects the percent down time or delays preventing their active operation (Figures 39 and 40). Net revenue decreases as utilization rates decrease due to fixed costs dominating more of the equation (Table 48). For the high, medium, and low efficiency systems the breakeven point was determined to be a 34%, 54%, and 63% utilization rate, respectively. This rate is only for the harvester and forwarders and not the layout, log loading, and hauling costs as they ran independently of each other post-harvest.

Change in Market Price of Sawlogs and Pulpwood

For the conditions observed at the study sites, a significant change in the market price of sawlogs or pulpwood would have to occur in order to cause an adverse economic impact (Figures 41 to 44). The current price at the time of the study being

$55 and $20 per ton for sawlogs and pulpwood, respectively, the sawlog prices were varied between $40 and $60 per ton and pulpwood between $10 and $30 per ton. The ranges used in the model run span the prices that have been observed in the region over the past decade. In the two studies conducted prior (Doyle 1997 and Brown 1995) pulpwood pries were slightly higher while sawlog prices were similar. If the stand had a lower percentage of sawlogs, then the impacts of the market price would be greater. Figure 53 provides and example for the high efficiency system only, of how this market effect combines with sawlog composition to alter the net revenue breakeven point (no cull or deduction was taken out in this example). As shown, with decreasing pulpwood prices, the need for a high percent sawlog composition is needed to breakeven.

Figure 53 Net revenue in dollars per ton for percent sawlog composition at different market prices for pulpwood.



Change in Species Removed

Species composition had a limited effect for change in species on net revenue. With the market price received being the same and the destination for log transportation for Douglas-fire and ponderosa pine being the same, the small effect on processing time by the harvester was the only variable effecting net revenue. If transportation costs or market price by species had differed, the effect of species would have been greater. No information was found in other studies that compared the performance differences amongst tree species. However, Raymond and Moore (1989) did find that limb size was a significant variable found to slow production and would account for some of the difference amongst the ponderosa pine and Douglas-fir species.

Change in Transportation Cost

Transportation costs made up approximately 20-30% of the total cost of the harvesting operation. As shown in Figures 47 and 48, as transportation costs increase due to longer haul distances or lower road standards, the revenues can rapidly decreased. If the net cost of harvesting and shipping to a mill is greater than simply harvesting and leaving the material at the site the latter option may be attractive. For example, given the current conditions at the study site, the pulpwood was costing the operation to harvest and deliver it to the mill. Assuming a log truck loaded to its legal weight can hold 25 tons and pulpwood is being purchased for $20 per ton, then each load receives $500 at the mill. Subtracting the loading and transportation cost on the average, it costs $625 to harvest 25 tons (enough wood for a log truck load based on $25 per ton for all associated harvesting costs but loading and hauling) and not transport it to the mill. By not delivering the pulpwood to the mill, the operation would then lose that $625. By delivering the 25 tons to the mill for a total cost to load and haul the material of $200 per load ($8 per ton with $2 for loading and $6 for hauling), the operation recovers $325 dollars per load over the option of simply leaving the harvested wood on site (given the market price of $20 per ton). With delivery, the operation then only loses $12 per ton on the average. This means that the hauling cost ($6 per ton) could be increased by three times its current level or, all things being equal, three times the distance. Any cost greater than this amount would create a higher loss than if the wood was cut skid and left on site for other disposal means or uses (and those costs would need to be considered as well).

Exchange Rate for Significant Variables

Using the derived equations from Figures 25 through 48 and their associated tables, an exchange rate was determined for related variables. On a per acre basis, under the conditions observed, the following exchange rate for variables that produced a positive effect on net revenue versus a negative effect on net revenue was constructed. Table 51 through 53 show how many units of a negative response variable it would take to equal the return from a positive response variable. In these cases only variables with a linear relationship were used.

To use the table, begin with the top row of positive net revenue response. After picking the variable of interest, move down the column. The numbers in the column are how many negative response units that the selected, positive response unit will off set or 'purchase'. For example, in the high efficiency system (Table 51) , one ton of live material would be needed to offset the net revenue loss of removing 3.10 tons of downed wood per acre, or you could pay $3.64 more per load if you could remove one additional ton of standing dead material per acre. These conversion values show the impact that positive and negative revenue factors have on each other, and provide a condensed and simplified version for the derived equations from Figures 25-48.

Table 50 Exchange rate for significant variables in the high efficiency system with respect to net revenue per acre.

Negative Net Revenue Response		Positive Net Revenue Response						
		Live[1]	Standing Dead[1]	% Saw @ 20[2]	% Saw @ 40[2]	% Saw@ 60[2]	Sawlog Price[3]	Pulp Price[3]
	Down[1]	3.10	0.79	1.08	2.15	3.30	3.00	1.14
	Hauling[4]	14.27	3.64	5.00	9.89	14.76	13.83	5.23

[1]Live, standing dead, and down material in units of one ton increase per acre.
[2]Percent sawlog composition in units of one percent increase per ton.
[3]Sawlog and pulpwood prices in units of one dollar increase per ton.
[4]Hauling cost for log trucks in units of one-dollar increase per load.

Table 51 Exchange rate for significant variables in the medium efficiency system with respect to net revenue per acre.

		Positive Net Revenue Response					
		Live[1]	% Sawlogs @ 20[2]	% Sawlogs @ 40[2]	% Sawlogs @60[2]	Sawlog Price[3]	Pulp Price[3]
Negative Net Revenue Response	Down[1]	27.46	12.86	25.46	39.38	35.32	13.36
	Standing Dead[1]	1.20	0.56	1.12	1.73	1.55	0.59
	Hauling[4]	10.76	5.03	9.97	15.42	13.83	5.23

[1]Live, standing dead, and down material in units of one ton increase per acre.
[2]Percent sawlog composition in units of one percent increase per ton.
[3]Sawlog and pulpwood prices in units of one dollar increase per ton.
[4]Hauling cost for log trucks in units of one-dollar increase per load.

Table 52 Exchange rate for significant variables in the low efficiency system with respect to net revenue per acre.

		Positive Net Revenue Response					
		Live[1]	% Sawlogs @ 20[2]	% Sawlogs @ 40[2]	% Sawlogs @60[2]	Sawlog Price[3]	Pulp Price[3]
Negative Net Revenue Response	Down[1]	2.23	1.59	3.16	4.72	3.55	1.34
	Standing Dead[1]	0.64	0.45	0.90	1.35	1.01	0.38
	Hauling[4]	8.68	6.20	12.30	18.38	13.81	5.23

[1]Live, standing dead, and down material in units of one ton increase per acre.
[2]Percent sawlog composition in units of one percent increase per ton.
[3]Sawlog and pulpwood prices in units of one dollar increase per ton.
[4]Hauling cost for log trucks in units of one-dollar increase per load.

While the variable, tree species was linear; it was not used due to its low level of impact on net revenue per acre. The significant variable diameter was not used due to its polynomial relationship and difficulty in manipulation for a management plan. Typically, stands are thinned from below and the level of thinning dictates the mean diameter removed. Utilization rate as well was not included due to variability based on a specific operator and operation. Taking the equations derived from the model a vast number of combinations and their relationships can be developed.

Mechanical Thinning and Prescribed Burning Decision Matrix

A flow chart of the primary decisions that were investigated for this study is shown in Figure 54. With the management plan, or stand objective, guiding the process and dictating the primary constraints for the treatment options, decisions were randomly assigned to a path (in the case of this study). While this shows the average outcome of the different possible treatments in this study, in reality the forest manager would need to explore the path that maximizes efficiency or revenue in more detail. In this study, the mechanical thinning portion of the treatment did return positive net revenue but, could it have been conducted in a more economically efficient manner? Further, if stand conditions change (i.e. more downed woody material), how would the economics of the individual treatments respond? This is where the question of maximizing efficiency and revenue comes into the flowchart (Figure 54) and where the derived equations from production and cost model or the exchange rates become useful.

In addition, maximizing efficiency does not necessarily mean making a profit (in contrast to maximizing revenue), however, it does mean doing the operation in the most economic manner possible while meeting all other constraints. The questions posed in the flowchart are those specific to the Hungry Bob study. Most of the questions are straightforward, and end with a cost and the question, "Was the objective met?" However, if maximizing efficiency or revenue is desired the use of the model output needs to be investigated to derive a potentially better solution.

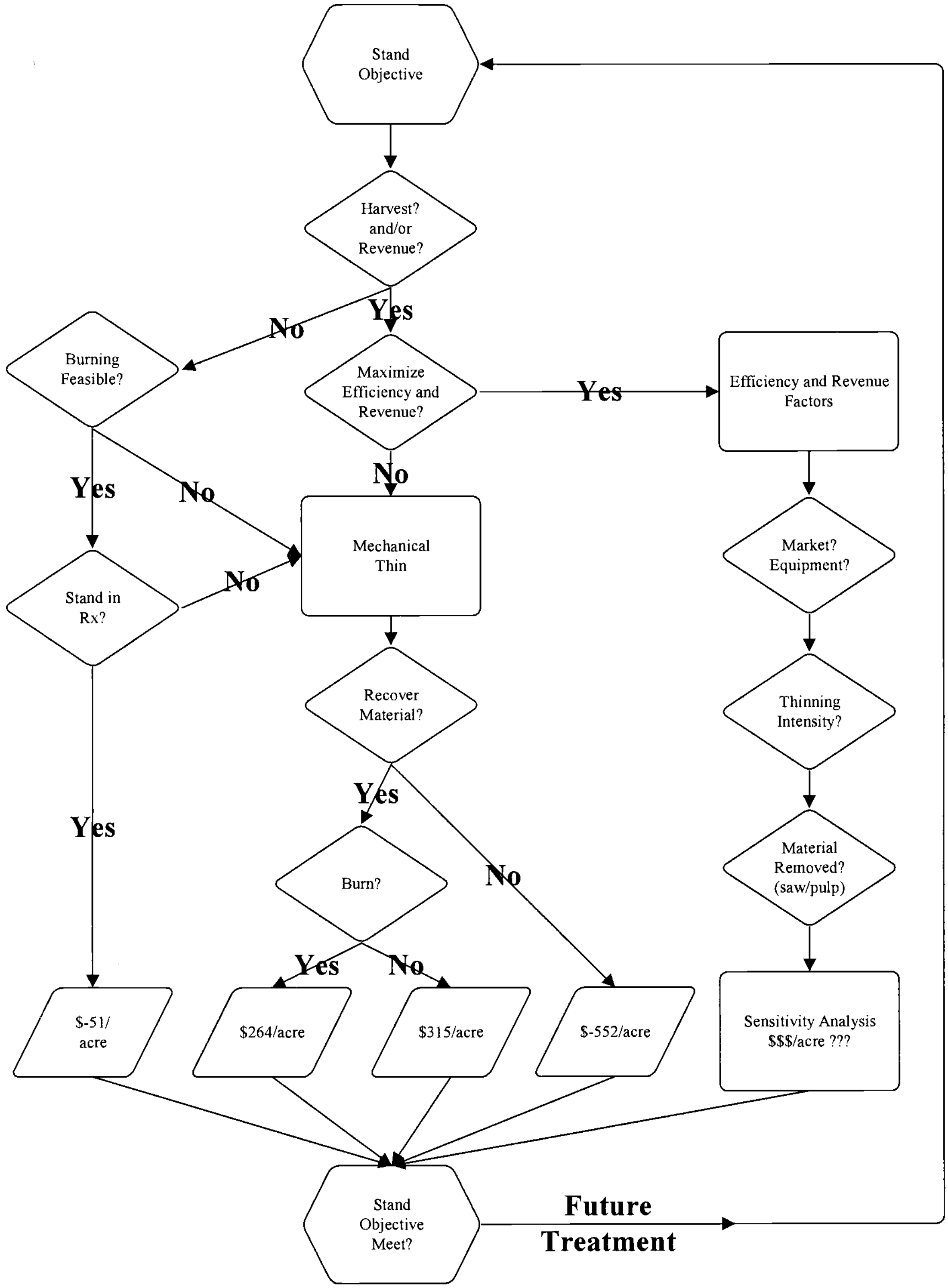
In Table 54, the modeling and decision making processes used for an individual stand type are broken down into three, semi-linked columns. The first is the prescribed fire only option, the middle option is the mix of thinning and thinning with burning, and the third is where the different alternatives are investigated. The stand objective begins the process and all decisions end with the question was the objective met.

The first question is whether harvesting or revenue is a desired product. Some areas around the study location would encounter considerable opposition to harvesting by the public or would not be physically feasible to harvest. These conditions or other reasons apply the initial answer no. This is followed by the next logical step which is to ask if burning is feasible. Unacceptable, adverse effects on wildlife, desired stand structure (due to current stand conditions allowing prescribed fire prescription limits), or the public are just a few of many reasons fire could not be prescribed. If burning is not currently feasible then the initial answer to mechanically thin the stands needs to be reconsidered or no option is feasible. If burning is feasible then the stand needs to be assessed as to whether it is in or out of prescription with respect to fuel loading without any pretreatment of fuels. If fuel loadings are too high, then some form of fuel reduction will need to occur, and this is suggested to be the mechanical thinning (again if thin is not feasible no option is available and alternative measures such as noncommercial fuel manipulation would need to occur). If yes a prepared burn plan would guide the operation and from the field study data the average cost would be expected to be $51 per acre.

Starting again at the beginning of the flowchart, if harvesting or revenue generation were an option, the pathway is then to either proceed with a similar approach to the field study, or look at others ways to maximize efficiency or revenue. If investigating alternative ways of maximizing efficiency and revenue is not a goal then a mechanical thinning should occur. The next decision is to determine whether the material will be recovered or left on site. Leaving the material in the forest would occur on a very limited basis and this option shows that the overall cost of bring the material to log decks next to the road is \$522/acre. As would be the case most of the time, recovery of material would be desired. The next decision then would be is whether burning is desired after the mechanical thin. If it is, net revenue of \$264/acre would be expected; if burning is not desired net revenue of \$315/acre would be expected.

Going back to the decision on maximizing efficiency and revenue, a yes answer would involve the use of the derived equations from the model simulations. To demonstrate the use of these equations we looked at a series of case studies. The results follow. Only a few key alternatives of the numerous possibilities were investigated. Manipulation of material removed and equipment selection can be the best approach for immediately improving the economic outcome. However, included in the decision process should be predicted market prices, equipment selection (including transportation), level of thinning, and material removed.

Figure 54 Mechanical Thinning and Prescribed Burning Decision matrix with outcomes from Hungry Bob (medium efficiency system).



Case Studied

A variety of stand conditions that occurred in and around the study sites were investigated by simulating costs based on the data acquired during this study. Stand conditions are stated for each scenario and a cost simulation was conducted for each. The prescribed fire costs are based on the average values determined from the study, and the cost to harvest is simulated using the production model. In all cases, the goal was to maximize revenue.

Based on the silvicultural prescription writing for the Hungry Bob Study (McIver et al. 1997), the following stand objectives were targeted. The stand objectives were to leave no more than 10 tons of downed woody fuel per acre and to reduce basal area through density management. In addition, the prescription was to leave dominant and co-dominant crown classes, allow wide distribution in space to account for natural clumps, retain all old, live trees greater than 21 inches DBH and remove competing conifers within 30 feet of dominants to prolong structural characteristics. The prescriptions were targeted to leave 70 to 80% of the pre-treatment tpa for ponderosa pine and 60 to 80% tpa for Douglas-fir.

Four common stand types were investigated for fuel reduction treatments with mechanical thinning, prescribed fire, or a combination of the two. Table 43 outlines the different stand conditions and variables that were targeted to meet the silvicultural prescription that occur among the four alternatives. These alternatives were open stand conditions, average stand conditions, large woody fuel accumulations, and dense stand conditions. In all cases, the medium efficiency system was used for determining mechanical thinning costs and net revenue as it best represented the span of equipment used onsite and was near the average of all three systems with respect to cost.

Table 53 Silvicultural stands targets to meet objectives used in constructing cost modeling of the four alternatives.

Stand Targets and Condition	Open Stand	Average Stand Conditions	Large Woody Fuel Accumulation	Dense Stand
Tons Live Removed	6.5	28	0	15
Tons Standing Dead Removed	0	2	10	15
Tons Downed Removed	0	0-10	20	0
Stems Removed per Acre	20	100-150	100	125
DBH Live	8"	8"	N/A	8"
DBH Standing Dead	N/A	7"	7"	6"
DBH Downed	N/A	7"	10"	N/A
Downed Woody Fuels Present	<5	10-15	>20	5-10

Scenario 1, Open Stand

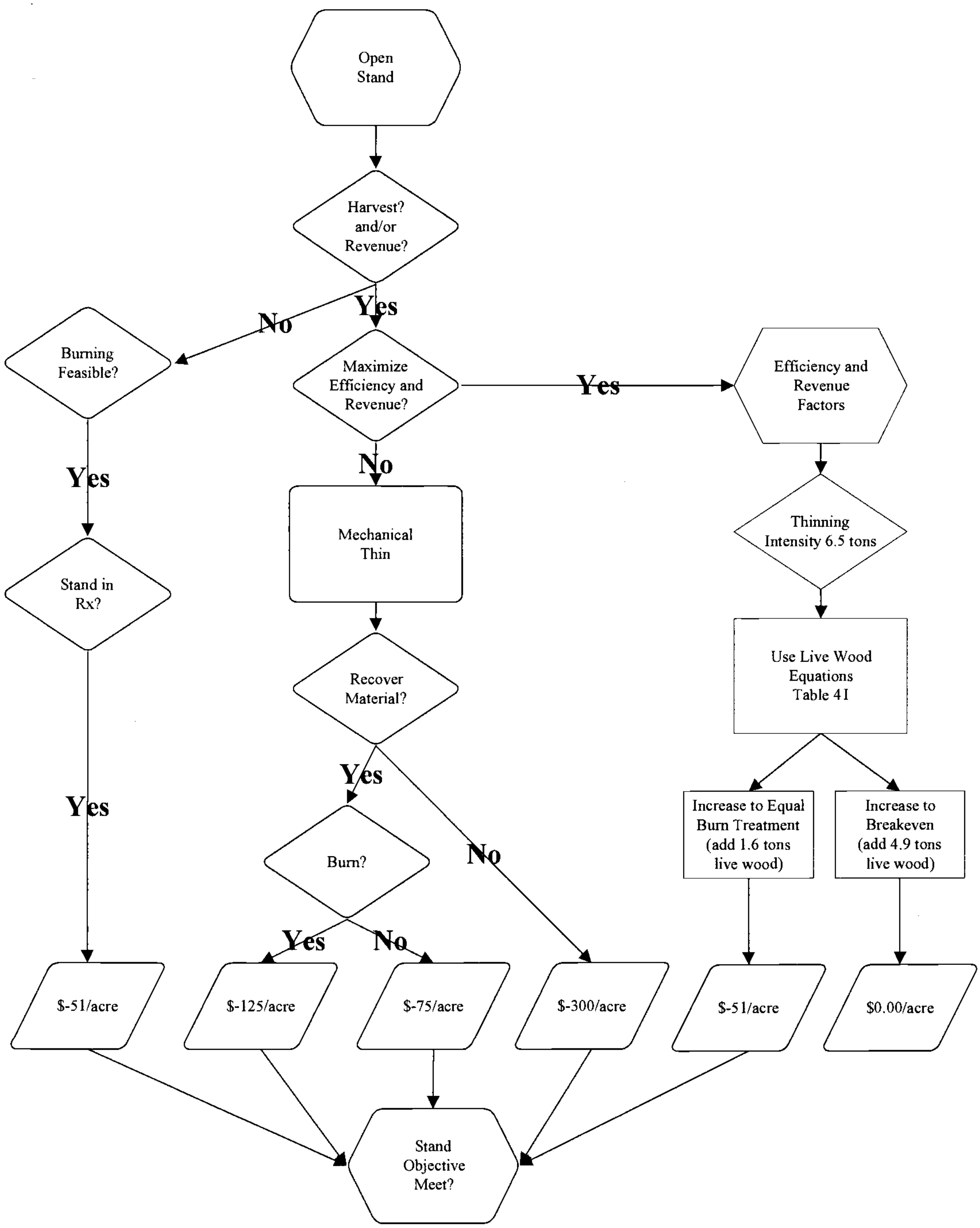
Areas with widely spaced trees, typically clumpy, and an understory assortment of grasses, herbs, and forbs were present in almost every study unit and larger areas with similar characteristics present throughout the broader landscape (Figure 55).

Figure 55 Open stand conditions in and around the Hungry Bob study area.

Fuel loadings in these areas were primarily the herbaceous accumulation and needle cast with minimal woody fuel (less than 5 tons). When these areas occurred in a study unit the mechanical harvesting equipment usually stayed out of the areas with extremely low stocking levels and entered open areas to harvest pockets or clumped areas within the open conditions. When a unit was burned, the prescribed fire lighting crew would burn through them. In the clumps of trees some thinning occurred, but on a very limited basis. Assuming, in this case, that 20 trees per acre could be mechanically harvested, on the average, the cost would be $300 per acre with average net revenue being a loss of $75 per acre. In this case, with the current stand objective, the thinning option would not be as economically feasible as an application of prescribed fire at $51 per acre. By using the equations derived from the cost model for live wood removal (Table 41) two alternative treatments were calculated. Using the medium level efficiency system the equation predicted an increase in net revenue of $15.38 per acre for every additional ton of live wood removed. With net revenue increasing as additional live wood is removed, the first alternative would be to decrease the current mechanical thinning cost to equal that of prescribed fire by taking additional material. Increasing the amount of live wood removed per acre by 1.6 tons 20%), the cost to mechanically thin goes from $75 to $51 per acre (equaling that of prescribed fire). The second alternative would be to lower the net revenue loss to zero. It would take an additional 4.9 tons per acre (75%) of live wood removal to create a zero net loss/profit.

Due to the low level of initial stocking levels prior to the treatment, these alternatives are likely not feasible as they might take the stand well outside its silvicultural object. However, this approach identifies that given the average stand and medium efficiency level live wood removal needs to be greater than 8.1 tons per acre to pass the cost of prescribed fire and 11.4 tons to break even.

Figure 56 Decision making process for open stand conditions in net revenue per acre for treatment options.



Scenario 2, Average Stand Conditions

Average stand conditions were described extensively in previous sections and the actual costs and revenue for the three treatments were reported (Figure 54). However, the question remains, "would it be possible to increase the revenue in these conditions?" With pre-harvest, downed woody fuel levels at approximately 10-15 tons per acre, fuels must either be mechanically removed or burned to meet the prescribed silvicultural objective. The average stand conditions are shown in Figure 57.

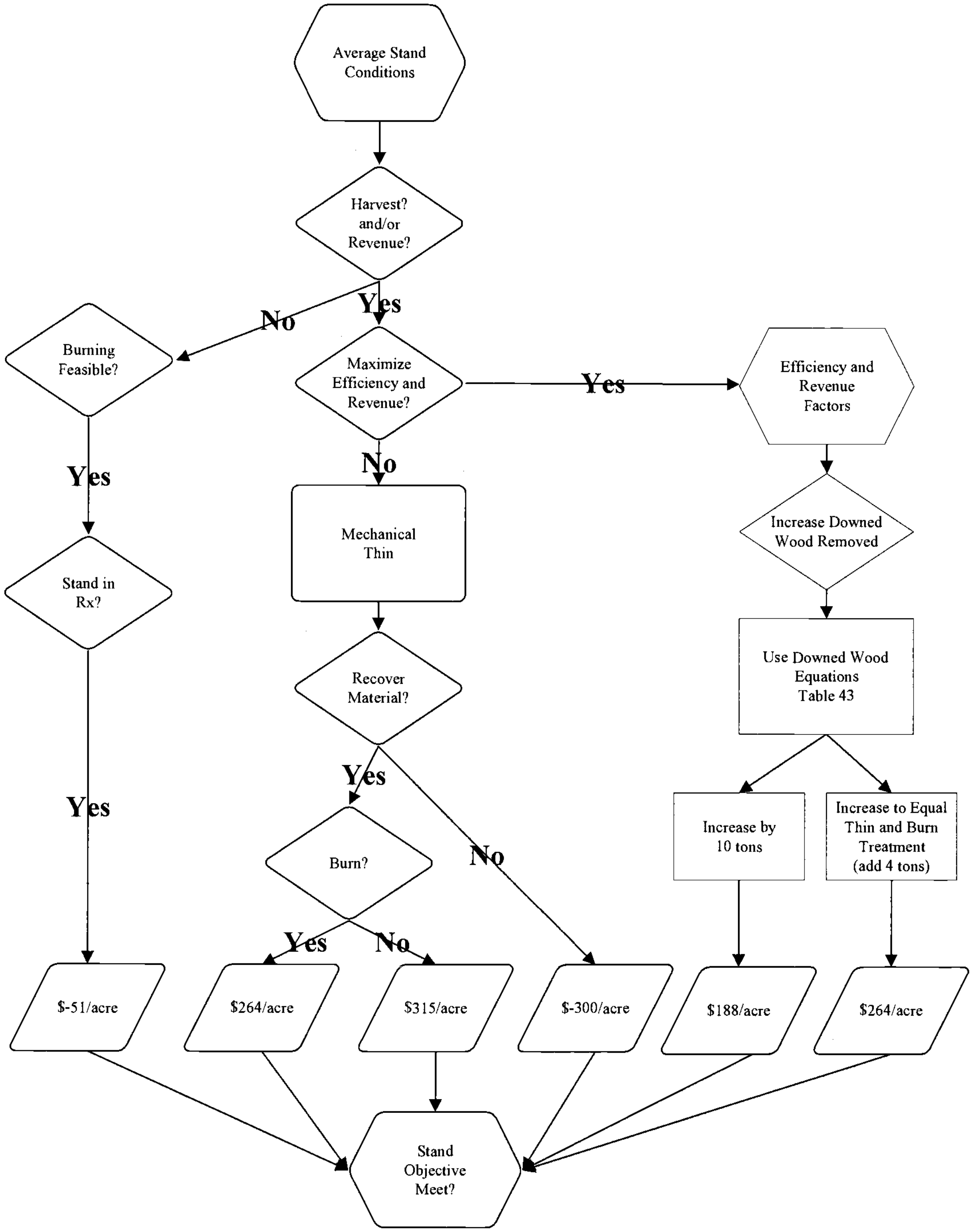
Figure 57 Average stand conditions in and around the Hungry Bob study area.

Burning the stand could be conducted (similar to the actual study) for $51 per acre, but the reduction in the overstory may not occur to the level targeted in the silvicultural prescription. If fuels reduction thinning occurred, to a level low enough to meet stand objectives, the cost would increase due to the higher removal level of the low valued downed wood. Using mechanical thinning to remove an additional 10 tons of downed wood per acre would reduce net revenue from $315 to $188 per acre (a decrease of $127 per acre). Shown in Figure 58, this alternative would indicate that the most economical method for reducing fuels and overstory density would be to thin and follow up with a prescribed fire producing an average net revenue of $264 per acre (a saving of $76 per acre).

For the medium efficiency system, net revenues are reduced $12.77 for every additional ton of downed woody fuel removed by mechanized harvesting. With a prescribed fire cost of $51 per acre, it becomes more economically feasible to use prescribed fire for fuels reduction when additional fuels removal (by the harvesting system) is greater than 4 tons per acre, as shown in the second alternative. Further, there is a direct savings of $12.77 for every ton of downed woody fuel left on site. If an area to be thinned is below the threshold limits of downed woody material (as prescribed in the burn plan) the material should be left on site to maximize the economic benefit of using prescribed fire. Developing the harvest plan and prescribed burn plan together would allow the mangers to prescribe cut to take and cut to leave trees (whether downed, standing dead, or live). Being able to evaluate the amount of activity fuels would need to be considered and with communication and training the operator, fuel loading post harvest could be managed as the harvesting is conducted.

The decision of how much downed wood could be left and burned on site, would be based on the current cost to conduct the mechanical harvesting (including planning to transportation costs) and what affect the downed wood has on that cost (i.e., the high and low efficiency systems). In addition, the percent saw logs to pulpwood that is produced from the material along with market price would need to be included. The model runs included in the previous section would be useful in determining these effects; however the model that was used to produce those comparisons would also be a useful tool to investigate the specific conditions being dealt with on other specific sites.

Figure 58 Decision making process for average stand conditions in net revenue per acre for treatment options.



Scenario 3, Large Woody Fuel Accumulations

Other portions in and around the study sites had areas with few overstory trees and higher levels of downed woody fuels (Figure 56). Pockets covering a few square feet to multiple acres had fuels ranging from 20 tons and higher on the ground. In the thin treatment these fuels were removed or reduced when thinned mechanically. When prescribed fire was used, these higher levels of fuel loading responded with increased fire intensity, thereby increasing the potential mortality to residual trees in proximity to the fuels. Figure 60 shows the fire activity approximately 10 minutes after the ignition of the area show in Figure 59.

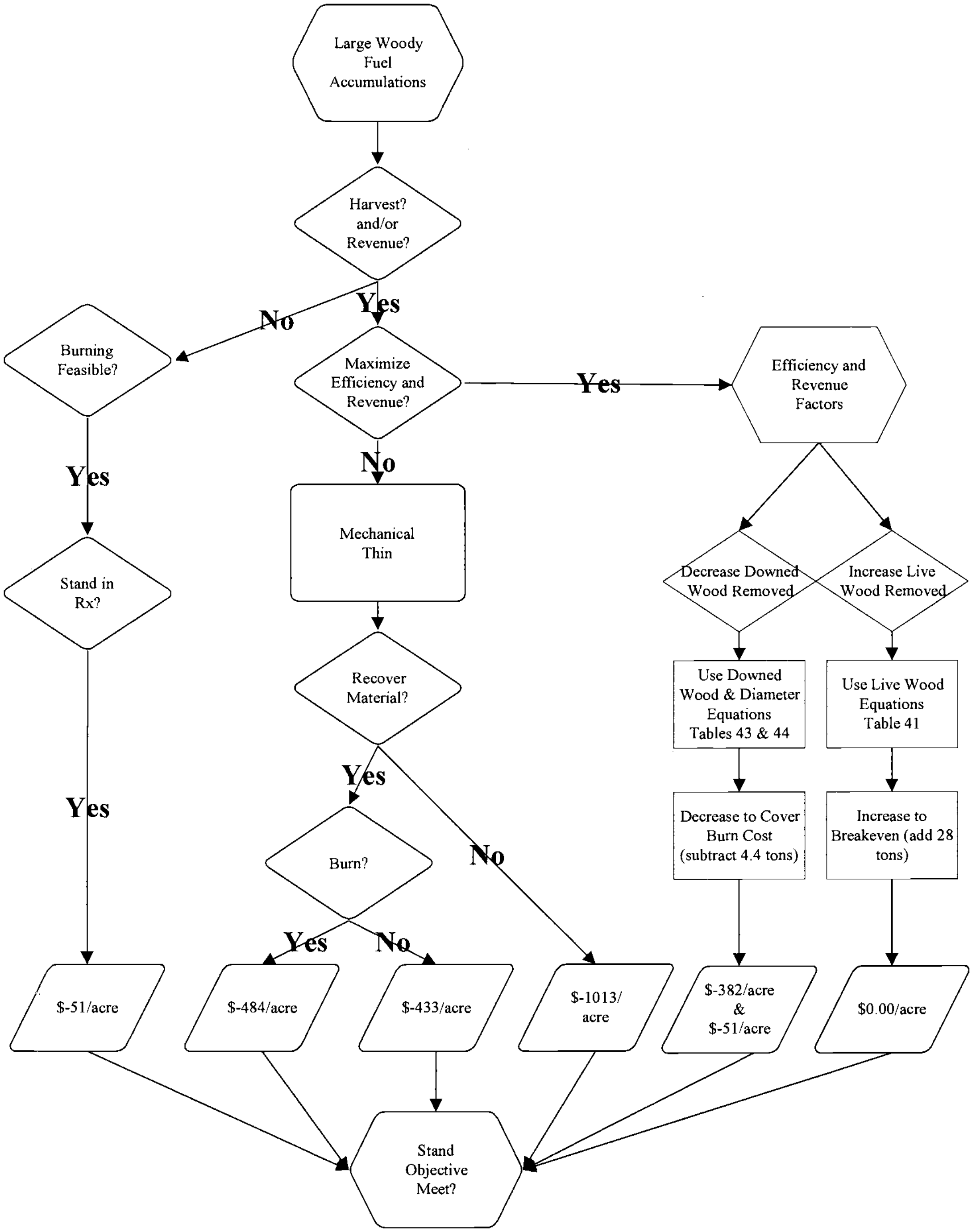
Figure 59 Stand containing clumps of large woody fuel concentrations in and around the Hungry Bob study area.

Figure 60 Fire behavior approximately 10 minutes after ignition by a prescribed fire crewmember as shown in Figure 59.

If the fuel loadings are predicted to produce adverse stand effects in the burn plan then pretreatment with mechanical thinning is needed. Many stands in the area and in past studies mandate the need for pretreatment of fuels. In the case of these stands in and around the study area, limited levels of standing live trees are present for removal and the primary source of material resides in the downed wood and standing dead trees. Given a downed wood removal of 20 tons per acre and a standing dead removal of 10 tons per acre the cost of the thinning operations would be $1,013 with net revenue at a loss of $433 per acre on the average. In this case, it is costing $11.50 for every ton of downed wood removed ($-12.77 for the downed wood and +1.27 for the increased diameter giving $11.50 and earning $0.56 for every ton of standing dead removed.

There are a couple of options, in this case, to consider for improving the economic outcome (shown in Figure 61). The first is to use prescribed fire in the same manner as scenario 2. By leaving 4 tons per acre of downed woody material on site the cost of the prescribed fire can be covered. Any amount over 4.4 tons left on site, would provide additional cost recovery over that for the prescribed fire and reduce the overall cost of the operations by $11.50 per ton per acre. This again would need to be planned in tandem with a harvest and burn plan. The second option is to allow an increased removal level of live trees. In this case however it would take over 28 tons (approximately 5 MBF) of live tree removal to offset the cost of the downed wood removal as a gain of $15.38 per ton of live tree is received. The concern however, is that the level of increased removal would not be feasible in most cases, so a combination of burning, leaving additional downed wood, and the potential to thin additional live trees would be a better solution. While the operation still produces a loss, if 5 tons of live trees were removed and the burn plan prescription required only 15 tons of the downed material removed (instead of 20 ton) the net loss per acre is $343 (which includes $51 for the cost to burn). The option, which is only one of many combinations of prescribed fire and thinning levels, produces an over all savings of approximately $141 per acre.

Figure 61 Decision making process for stand conditions with large woody fuel accumulations in net revenue per acre for treatment options.



Scenario 4, Dense Stand Conditions

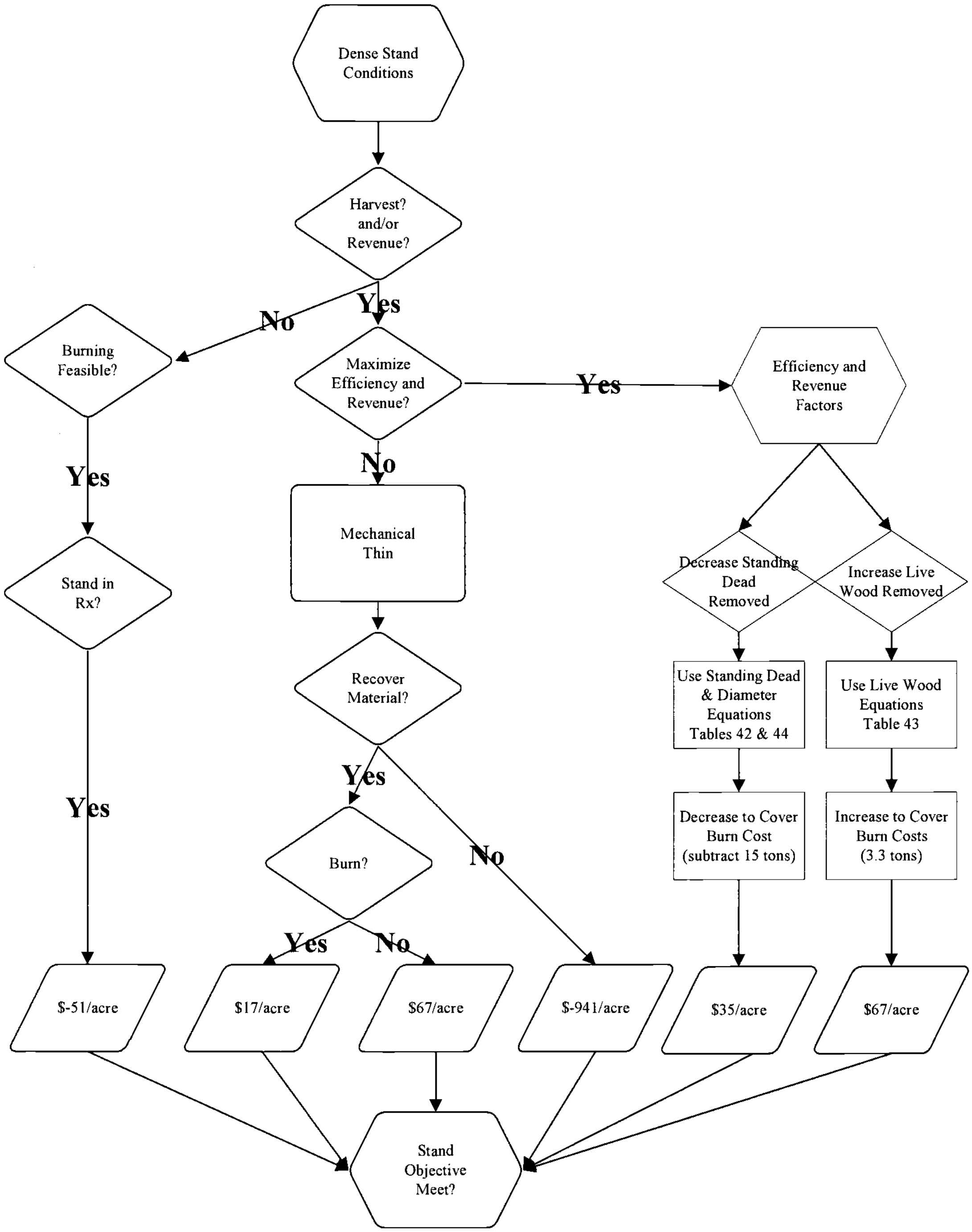
The last common stand type that occurred in and around the study area were dense thickets of small suppressed Douglas-fir and ponderosa pine being over topped by a few large ponderosa pines and to a lesser extent fir (Figure 62). In these stands, there is limited downed woody material and most of the dead material has remained standing. The targeted amount of live and standing dead removal for this stand type would be around 15 tons per acre for each.

Figure 62 Dense stand conditions in and around the Hungry Bob study area.

In addition, these stands have a smaller average diameter in the standing dead material and a larger diameter in the dominant trees compared to the conditions in the average stand. We used an average diameter of 6 inches for standing dead material and 8 inches for the live tree removal. A cost of $941 per acre and net revenue of $67 per acre was found. The cost to remove the smaller diameter standing dead material would be $1.26 per ton per acre (using both the standing dead equation from Table 42 and the diameter equation for Table 44). In order to pay for the prescribed fire cost by leaving additional fuels it would take 40 tons of standing dead to be retained in the stand. Since only 15 tons of standing dead material is present, this option would not be feasible (Figure 63).

If the site needed to be burned post harvest at a cost of $51 per acre, a $17 per acre net revenue would remain and the operation would still produce a positive return. However, it would only take an additional 3.3 tons of live wood removal per acre to cover the cost of the prescribed fire as live wood is providing a net revenue per ton removed of $15.4 per acre. Again the best way to view this stand from an economic sense would be to complete a burn plan and set the constraints that the mechanized harvesting operations can work in.

Figure 63 Decision making process for dense stand conditions in net revenue per acre for treatment options.



Recommendations

In this study, mechanized thinning and prescribed fire were the only two options investigated for the treatment of fuels and promoting forest restoration. It is important to note that the modeling efforts and regression equations be applied to stands of similar type and within the range of stand conditions observed. As was shown, the production and associated cost for the different equipment combinations produced a range of costs and production rates, which does span a wide range of equipment currently available. In the stand conditions observed over the study area, all combinations of equipment were effective at reducing stand density and received a positive economic return. From the results, it was indicated that the Rottne single-grip harvester and Timbco forwarder were by far the best choice of equipment (based on cost). However, it is important to understand what type of equipment is available and its location with respect to the treatment area. Using the results to both select equipment and understand the limitations of machinery that is currently available are both important points that need consideration.

When multiple pieces of equipment are available to operate within an area, it is important to understand and match their performance characteristics to stand conditions to obtain the most benefit. While the information provided shows the performance capabilities and how stand conditions can effect production and cost, it is usually necessary to investigate specific machinery being proposed. By looking at the production rates in different stand conditions, similar relationships could be determined as to what conditions are best suited to the specific machine. As more data is collected in this area, information will become available on what equipment features and attributes are best for specific material being removed and stand conditions. A more robust database on equipment performance and productivity will lead to a better understanding of the fuel reduction economics.

However, if equipment selection is limited, stand prescriptions could be modified. Rather than prescribing pieces of equipment to stand conditions, alterations to the silvicultural objectives could be made to better suit available equipment. By using available stand data and gathering specific equipment details including thinning levels, type of material being removed, and volumes (per acre) silvicultural prescriptions or stand objectives could be modified to produce higher compatibility between silvicultural prescription and harvesting equipment. While modifications to the stand objectives would need to be investigated (based on meeting the goal of fuels reduction and forest restoration), a very small change in the percent live tree removal or reduction of downed wood removal (for example) could make a system profitable rather than produce a loss. Knowing the equipment being used, its performance capabilities (especially with respect to material being removed), and the stand conditions it will be working in are essential to effective harvest planning.

Prescribed fire in stands that have a low level of downed woody fuel as well as lower stocking levels can be used alone without any pretreatment of fuels. It will not be know for a few years what the overall effects of prescribed fire on reducing stand densities, but even with the best burn plan and conditions it is difficult to predict the actual fire effects on a residual stand. However, the cost of prescribed fire applications is considerably less than the cost of mechanized harvesting in certain circumstances (as shown in the case studies). If economic losses are being incurred through harvesting, the use of fire may provide a cost effective alterative.

While all the study units could have been burned, many stands around the area would require pretreatment of downed and standing fuels before burning. Use of mechanical thinning for pretreatment also produced residual, activity fuels which can have a significant effect on fire intensity. A few changes, however, can reduce the overall effect of the residual slash in the stand. The first consideration is how the mechanical felling is conducted. The operator of the single-grip harvester should avoid processing and accumulating large amounts of slash next to the residual trees (particularly the dominant larger trees) or in continuous strips of connecting fuel. Operators should be instructed to swing the boom (with tree) to an opening or a few extra feet away from a residual tree, thereby reducing the effects of high fire activity next to the base of the tree. This would add very little costs to the operation, as it would only take a couple of seconds at most. The next effort to avoid undesired slash accumulations would be to mark, 'no slash zones' in the harvest unit. Putting paint on leave trees could delineate a given fixed radius around the tree in which slash must be kept clear. Further, the operator could remove any preharvest slash from these areas if it is already present.

While trying to manipulate the slash within the stand to avoid damage or mortality to residual trees for a post thinning burn, slash could also be used to remove standing dead and smaller live trees during the burn. Rather than whip falling the stand or spending time mechanically thinning non-merchantable pole sized trees, operators could be instructed, or marking could be placed in areas where higher fuel loading is desired, to increase the localized fire intensity. This technique in tandem with the no slash zone could help better control and meet the stand objectives while potentially reducing the cost of felling non-merchantable material.

Another resource implication is the occurrence of tree wounds. Wounds that remove the bark on the lower bole of the tree produce accumulations of resin and pitch that may ignite during the prescribed burn. Proper residual tree spacing, reducing the amount of machinery movement in the stand, matching the equipment to the size of material being removed, and improving operator awareness is needed to reduce levels of stand damage.

Planning is the most important component given the potential fire effects issues with respect to slash and stand damage. When using mechanical thinning with fire, development of both the harvest plan and burn plan together is the best way to insure that the stand objectives are optimally achieved. Adverse interactions can be addressed, modifications can be made and to the mutual benefit of both operations. Further, if the economic outcome can be viewed as a total system, then fire can be used fully to aid and potentially reduce mechanical thinning costs.

To aid this decision-making process production and cost model was constructed. While the cost of prescribed fire was calculated, there was very limited information to support the prediction of prescribed fire cost given the variables investigated. Due to the costs associated with prescribed fire and the lack of revenue generation, its economic structure is more basic than mechanical harvesting. In addition, when compared to the costs of mechanized harvesting, prescribed fire costs are considerably lower and less variable. Rather than predicting a cost for the total operation, it is better to first determine the cost of thinning then look at how much fire could cost. With operation objectives of breaking even, not exceeding a given cost per acre or ton, or setting a minimum revenue per acre or ton required, a maximum allowable cost could be determined for the prescribed fire operation. This predicted prescribed fire cost would allow the fire manager to budget for the future prescribed burn plans. In addition, if some operations produced a revenue surplus after harvest and burning and others a loss, these could be combined and an average cost per acre used. If revenues from the thinning operation could be used to carryout the burn plans, more acres could ultimately be treated. It is recommended that land managers keep track of production information and the appropriate operating conditions; even simple information will help in future planning efforts and cost modeling.

Summary for Land Managers

A summary of key points that land mangers need to be aware of when conducting these types of harvesting activities is presented and suggestions for harvest planning and activities during the operation are outlined below. This is only a summary of the information provided within the text of this study and not all inclusive. Detailed results and discussion of individual variables were presented earlier.

During the harvest planning stage equipment selection and associated costs need to be known or developed. In addition, how the individual pieces of equipment responded to stand conditions must be understood in order to design the silvicultural prescriptions. Matching equipment to a prescription can be challenging if equipment is limited in the region or area of the harvesting activity. Knowing the factors that affect the economic feasibility of equipment and planning in tandem with the silvicultural prescription will enhance the potential for a successful economic return or reduced losses.

Live trees, standing dead trees, and downed wood have an impact on harvester performance as well as their market value at the mill. When writing the marking guidelines for the stand, slight modifications in the silvicultural prescription can have a profound affect on the net revenue. By using the value of the live wood, land managers can offset the costs of harvesting the lower valued material and in many cases produce a better economic condition for logging contractors and landowners.

The percent sawlogs to pulpwood ratio that is produced from the mix of material removed is the best way to simplify the material classification when looking at live, standing dead, and downed wood economics. Deriving the breakeven point for a typical stand type and piece of equipment (with respect to percent sawlogs) should be conducted as operations occur in the area. Using the log truck scale ticket information and collecting some daily or weekly shift level data would provide insight for determining this point over time.

Transportation costs and a market for the material removed is also import to include in harvest planning cost calculations. Stand location with respect to the mill's destination can produce a significant cost as transport distance increases. As mill locations in many of these areas decreases, there is a direct impact to net revenue. In addition, the market demand and price received needs to be predicted with some level of confidence and included into the equation in order to fully develop the cost calculation.

Prior to harvesting the stand, marking guidelines need to be more specific than tree spacing, residual densities, and species if prescribed fire is to be used post-harvest. Incorporating a marking design that indicates where (in the stand) activity fuels and slash should be avoided or removed would better facilitate the effectiveness of the prescribed fire burn plan and would aid in reducing residual mortality. Keeping fuels clear of large dominant residual trees, snags, and large downed wood needs to be addressed by either putting marks on the ground or through communication and written understanding with the logging contractors. By modifying fuels location, the prescribed fire intensity could be lowered around areas where there is the desire to increase the retention of woody structures and reduce mortality after a prescribed fire. A recommended distance and marking protocol would need to be determined for the stand conditions that the fire was applied under and training of both marking crews and logging contracts would be needed.

Another management consideration prior to harvesting is the marking of designated skid trails. To prevent the occurrence of a large flaming front and increased fire intensity during the prescribed fire, trails should be marked so activity fuels are not allowed to run in continuous strips parallel to the slope. On the steeper slopes, trails will typically run perpendicular, but on flatter ground trails tend to run at random directions. Working with the prescribed fire manager on how the unit will be burnt would provide the needed information to potentially avoid having strips of fuel (generated by the harvester) running along a proposed prescribed fire line.

During the harvesting activities, attention should be made to the level and type of residual stand damage. Reducing the number of open pitchy wounds is important if prescribed fire is going to be used. If levels of stand damage are too high, changes should be made to residual tree spacing, equipment selection, and operator education on future operations.

Lastly, the information provided in this study should form a foundation for building a site specific, systems database.

Future Research Work

Future work is suggested in two areas; fuels reduction methods and research methods. Two suggestions in each area are provided. Future research needs to investigate a wider range of fuels removal than we have included in this study. Developing a more robust data set would provide higher levels of understanding as to the interactions of harvesting systems with fuels loading, placement, and arrangement. A variety of different harvesting systems are being investigated around the country in the area of fuels reduction economics and environmental impacts. By adding more variability through differing levels of fuels removed and harvesting systems, a better understanding of how and where these systems should be used will be better understood. Information on a broad scale of harvesting systems will develop over time (through the fire, fire surrogate study) and there will be a limited need for new commercial timber harvesting research (McIver and Matzka 2002). However, the need to investigate non-commercial fuels reduction with lower cost systems would be a beneficial area of focus.

A new computer program for collecting production data should be developed. The development of handheld computers and integrated, low cost global positioning systems (GPS) and the Microsoft Windows CE programming language could lead to the integration of a time study program with a GPS system. This would provide a spatial analysis component to the data as well as simply making data collection easier and more detailed.

The construction of the heat tiles could be improved. The red cinder ceramic tiles were difficult to produce. A single mounting hole was drilled into each of the 400 tiles with this drilling process taking over 30 high quality mason drill bits and 5 minutes per tile using a drill press. A larger whole (1/4" in diameter) relieved the problem of tiles breaking and speeded up the mounting hole, drilling process. However, in retrospect, a 6" square piece of aluminum sheet metal would have been easier to mass produce, but more importantly would have allowed a faster reaction time over the ceramic tile (due to the lower mass and better heat transfer). A thick enough piece of sheet metal would be needed so that the tile did not melt.

Conclusion

In the stand conditions observed, three distinctly different single-grip harvesters and forwarders produced significantly different production rates. A purpose built Rottne SMV Rapid EGS, purpose built John Deere 653C, and retrofitted Caterpillar 320L excavator produced production rates of 22.2, 21.6, and 16.3 tons per SMH, respectively, in average stand conditions. Differences between the purpose built and retrofitted machines and their associated processor head design, boom configuration, and wheel or track type contributed to performance differences. Hourly ownership and operating costs for the single-grip harvesters ranged from $186 to $263 per acre or $6.0 to $8.4 per ton for the removal of predominantly merchantable timber. Significant variables that affected production rates were found to be: volume of live, standing dead, and downed material removed, tree species, distance traveled between processing, and stem diameter.

Production for the Timbco forwarder was 0.24 loads per PMH more than that of the two Rottne SMV and Rottne forwarders. Production rates for tons per SMH were 20.9, 12.5, and 10.0 for the Timbco, Rottne SMV, and Rottne Rapid, respectively. These production levels equated to hourly ownership and operating costs for the forwarders ranging from $150 to $294 per acre or $4.8 to $9.4 per ton. Significant variables that affected production rates were found to be: distance traveled and the numbers stops required to accumulate a full load for the forwarders. Evidence to explain the varying production rates was limited and based primarily on operator experience and machine design.

Prescribed fire costs ranged from $24.4 to $87.3 per acre. The average cost in the burn and thin and burn units were $48.8 and $56.8 per acre, respectively, with an average cost per acre of $50.5. Cost was affected by both treatment type and unit size; the larger the unit size the lower the treatment cost. Lower treatment costs were also predicted for the burn only units.

Prescribed fire intensity was found to be significantly higher in the thin and burn units with tons of downed woody material being a significant predictor of fire intensity. Mean fire intensity was 94.7 and 157.6 degrees Celsius for the burn and thin and burn treatments, respectively. The addition of activity fuel from the mechanical thinning was the main factor that increased fire intensity.

Predictive equations were used to construct a cost model that investigated different stand conditions of significance. The effects on production and cost of differing levels of live tree, standing dead, and down woody removal could be analyzed. In addition, material diameter, percent sawlogs versus pulpwood, utilization rates, species composition, and transportation costs could be investigated. This model and its output provides information that a land manager can use to assess the economic feasibility of a given operation.

This study provided quantitative and qualitative insight to the factors affecting the economics of fuels reduction and forest restoration in the dry forests of the Blue Mountains located in northeastern Oregon. Efforts in fuels reduction and forest restoration need increased levels of planning as the products removed are typically lower value sawlogs and pulpwood. When the use of thinning and prescribed fire are tools the land manger can use in tandem, they need to be viewed as a whole system since economic synergies can be achieved.

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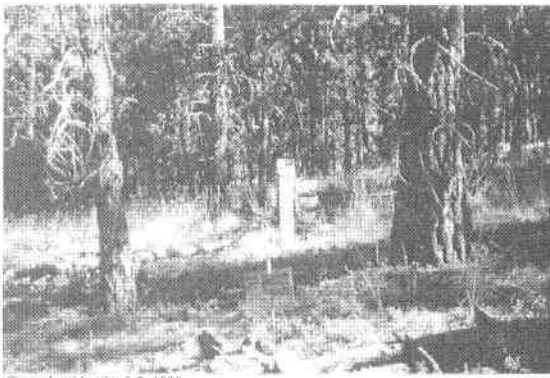
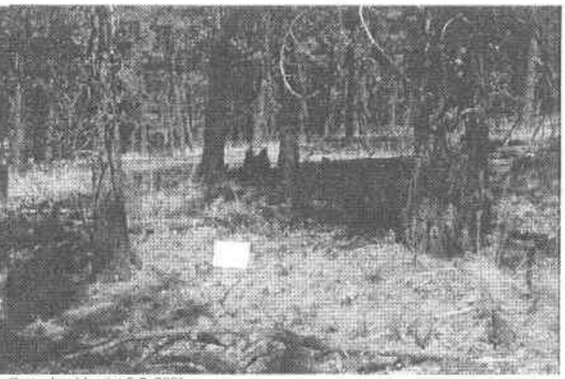
Appendices

Appendix A Photo Series of Treatment Units

Figure 64 Unit 2, 4, and 5 Control



Control, grid point 5-2, 1998



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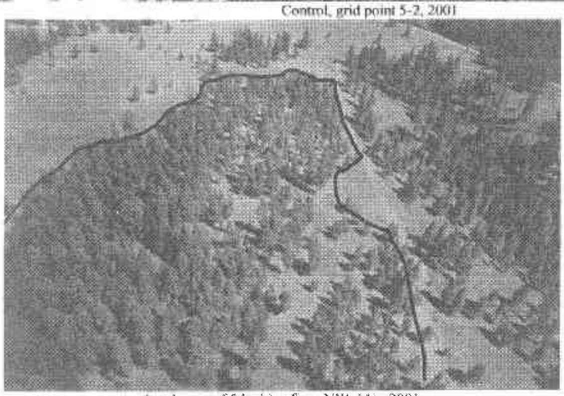
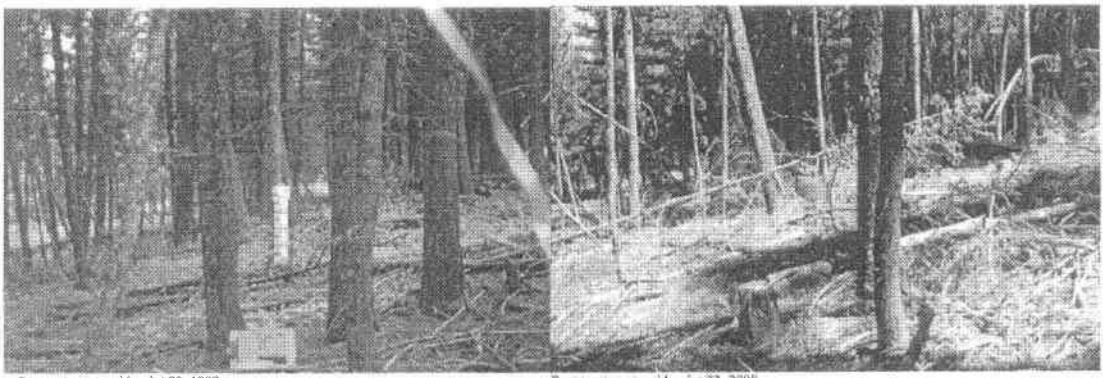
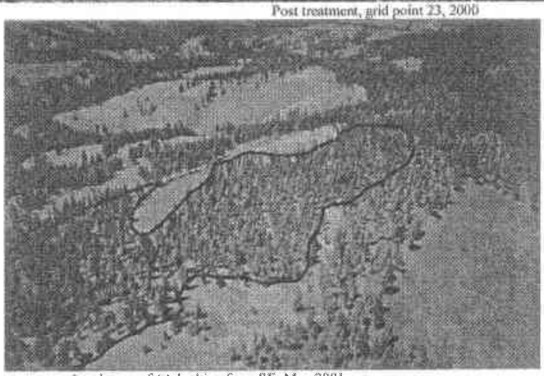


Landscape of 5 looking from NW, May 2001

Figure 65 Unit 6a Thin

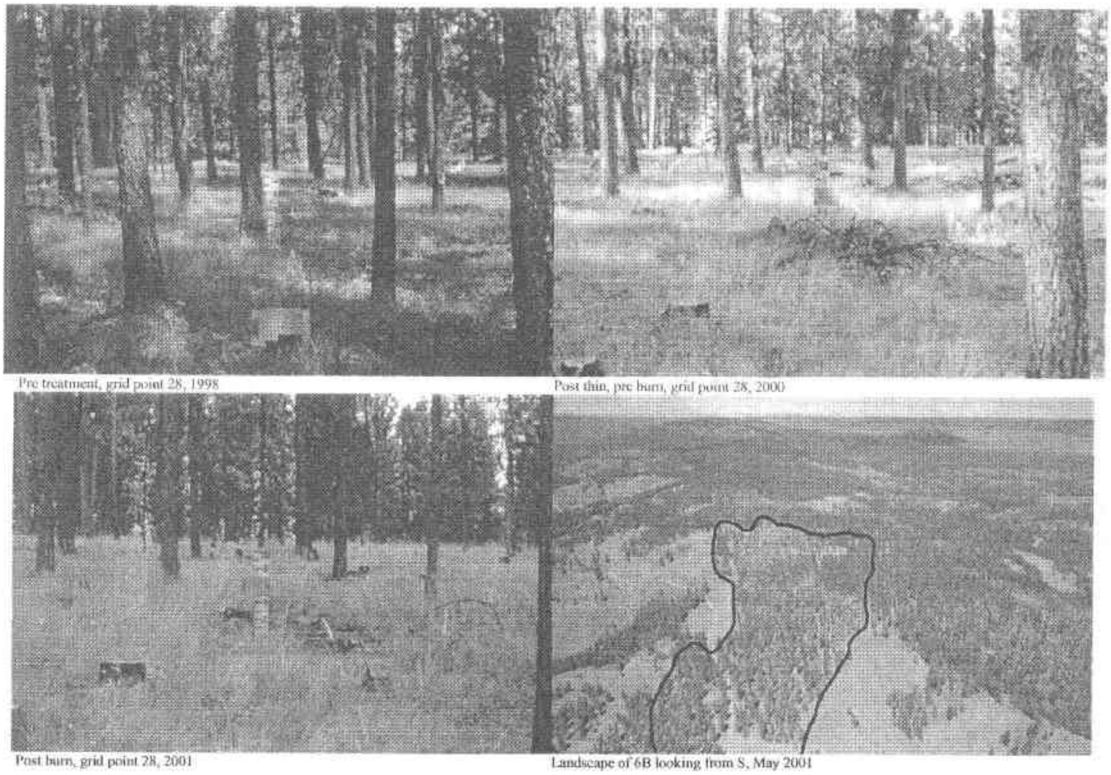


Pre treatment, grid point 23, 1998 Post treatment, grid point 23, 2000



Landscape of 6A looking from SE, May 2001

Figure 66 Unit 6b Thin and Burn



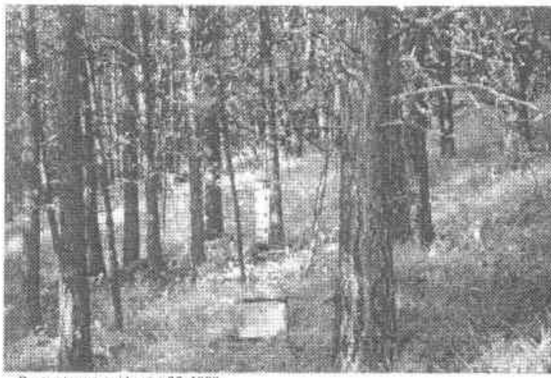
Pre treatment, grid point 28, 1998

Post thin, pre burn, grid point 28, 2000

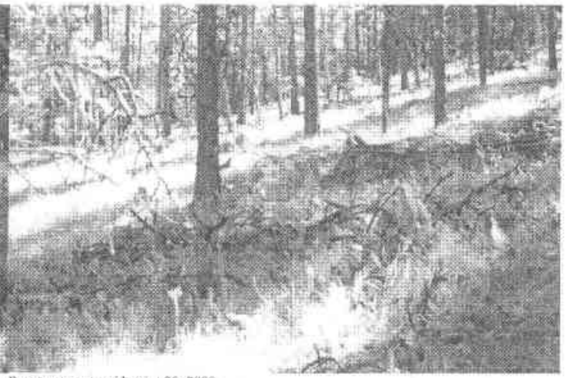
Post burn, grid point 28, 2001

Landscape of 6B looking from S, May 2001

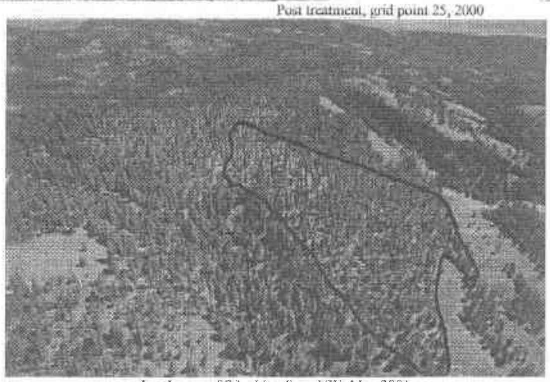
Figure 67 Unit 7 Thin



Pre treatment, grid point 25, 1998

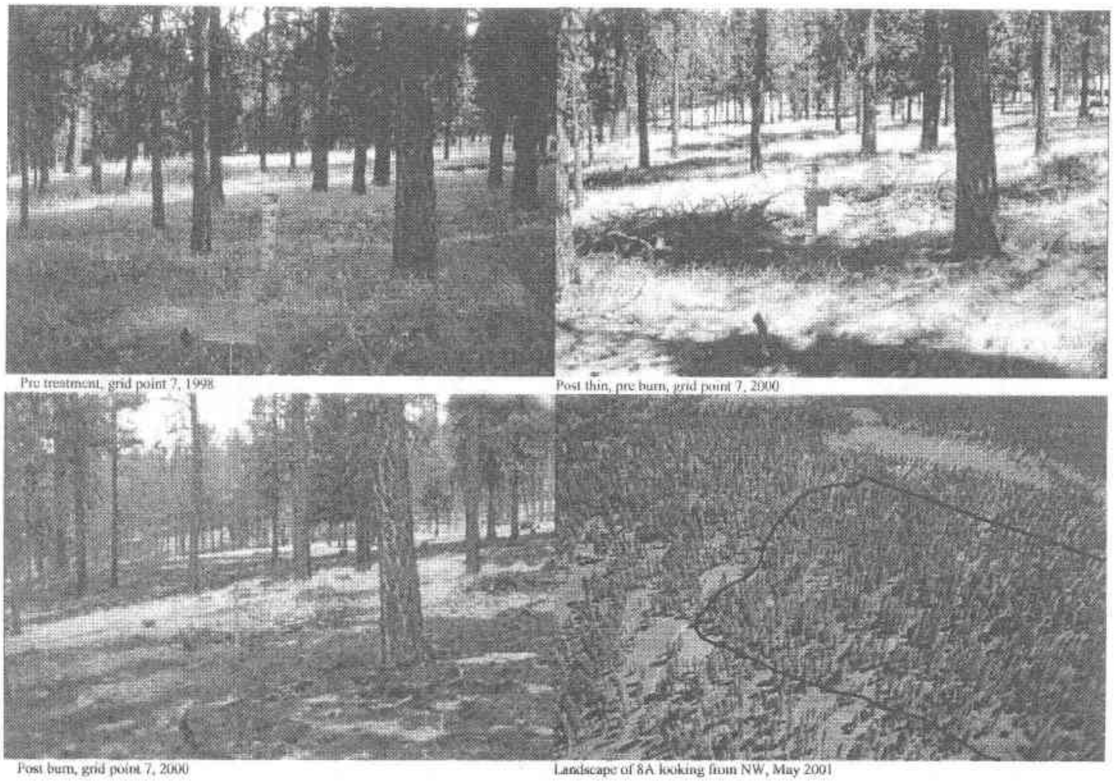


Post treatment, grid point 25, 2000



Landscape of 7 looking from NW, May 2001

Figure 68 Unit 8a Thin and Burn



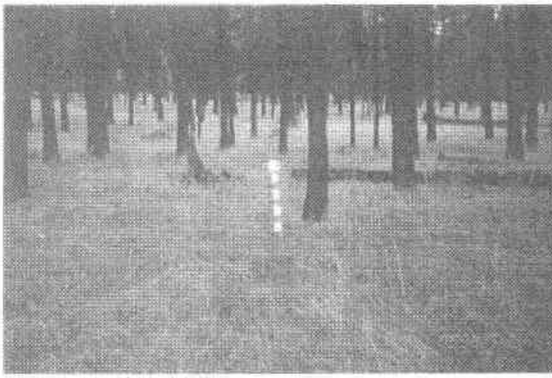
Pre treatment, grid point 7, 1998

Post thin, pre burn, grid point 7, 2000

Post burn, grid point 7, 2000

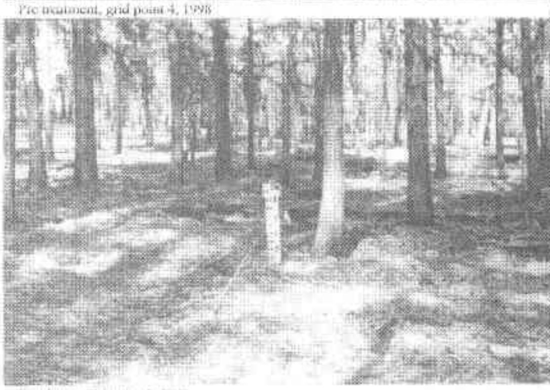
Landscape of 8A looking from NW, May 2001

Figure 69 Unit 8b Burn

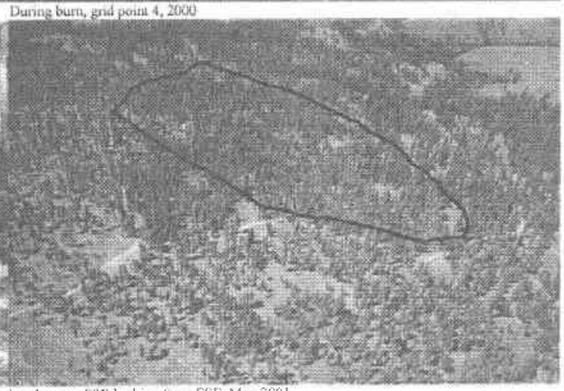


Pre treatment, grid point 4, 1998

During burn, grid point 4, 2000

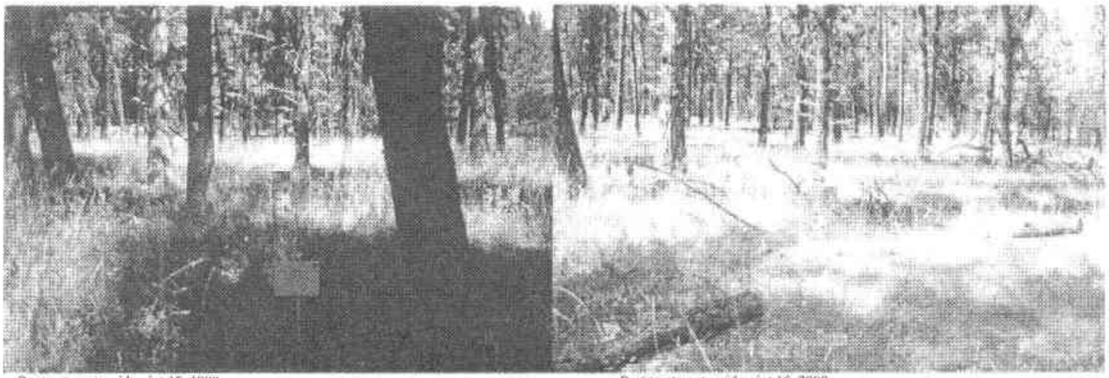


Post burn, grid point 4, 2000



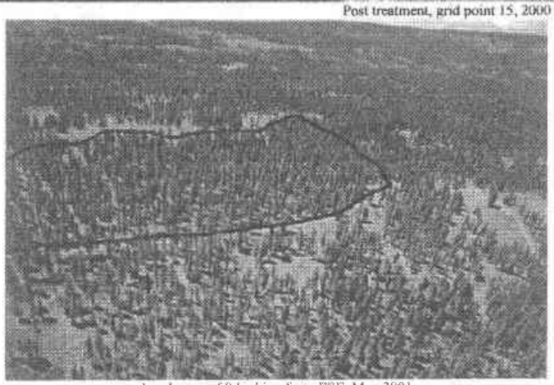
Landscape of 8B looking from ESE, May 2001

Figure 70 Unit 9 Thin



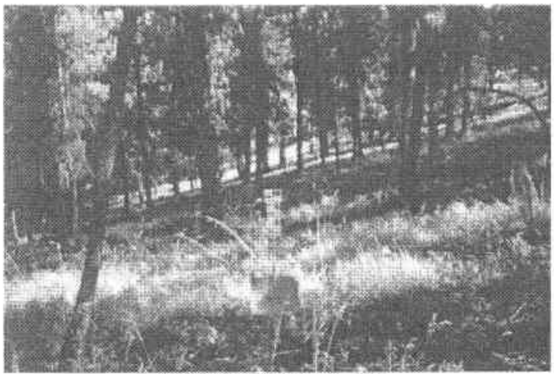
Pre treatment, grid point 15, 1998

Post treatment, grid point 15, 2000

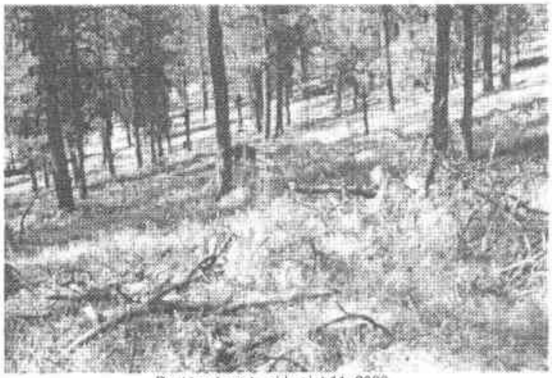


Landscape of 9 looking from ESE, May 2001

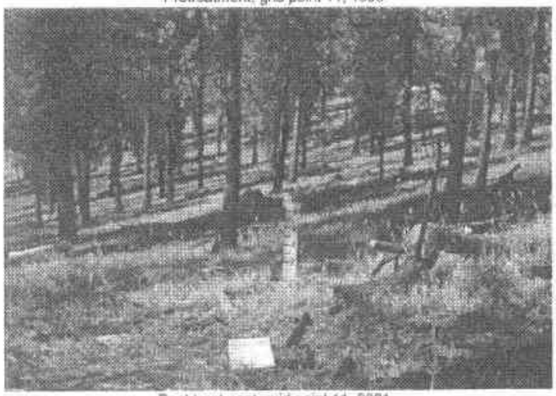
Figure 71 Unit 10a Thin and Burn



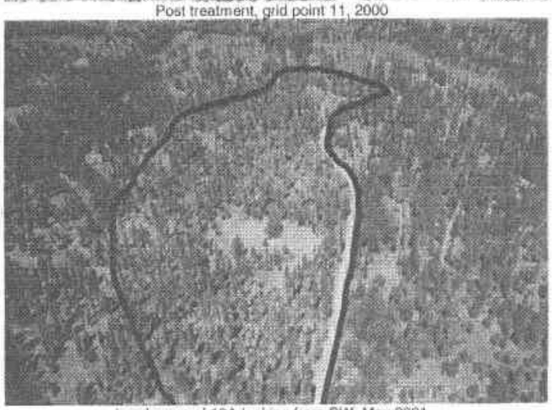
Pretreatment, grid point 11, 1998



Post treatment, grid point 11, 2000

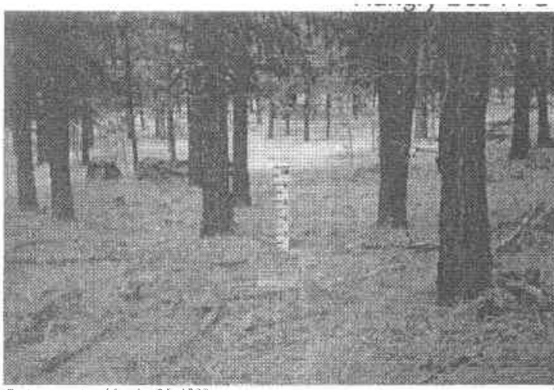


Post treatment, grid point 11, 2001



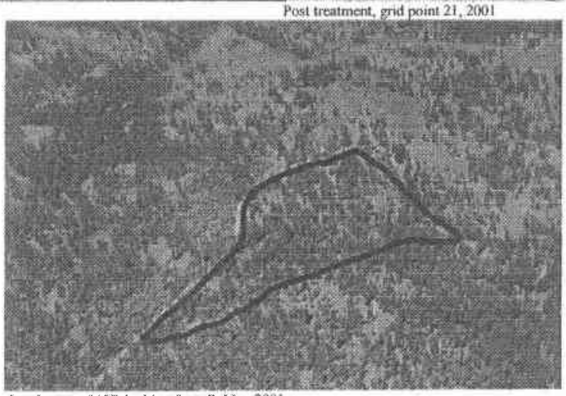
Landscape of 10A looking from SW, May 2001

Figure 72 Unit 10b Burn



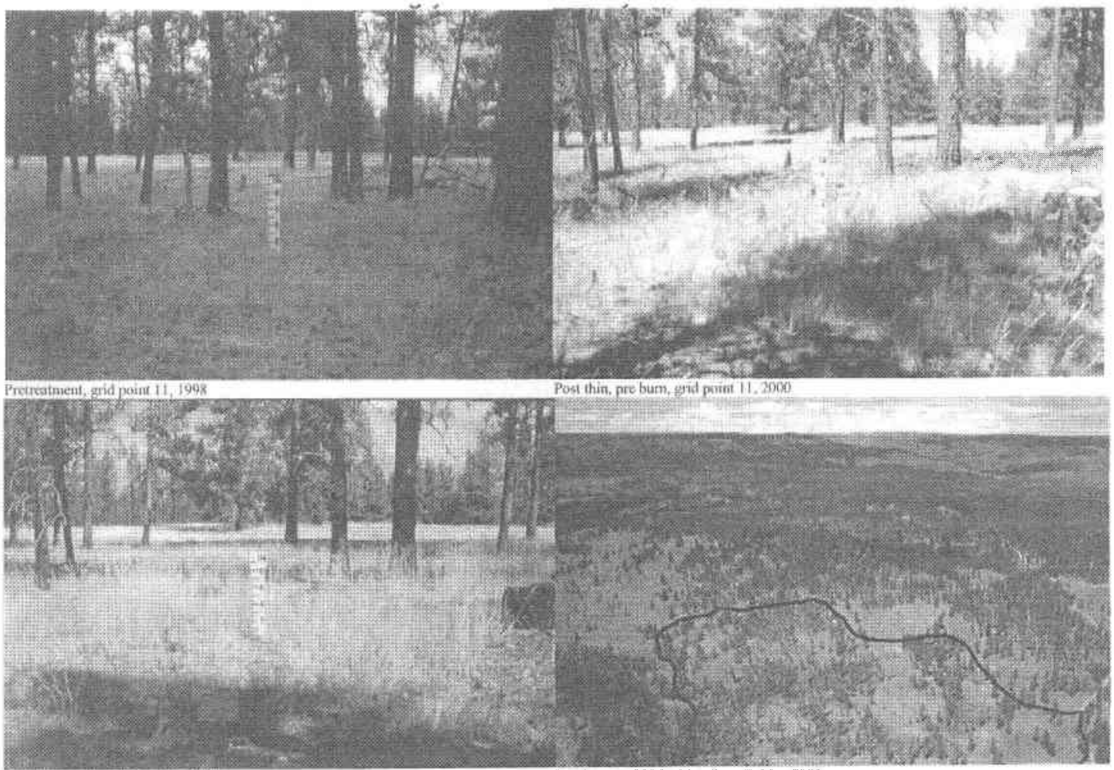
Pretreatment, grid point 21, 1998

Post treatment, grid point 21, 2001



Landscape of 10B looking from S, May 2001

Figure 73 Unit 11 and 12 Thin and Burn



Pretreatment, grid point 11, 1998

Post thin, pre burn, grid point 11, 2000

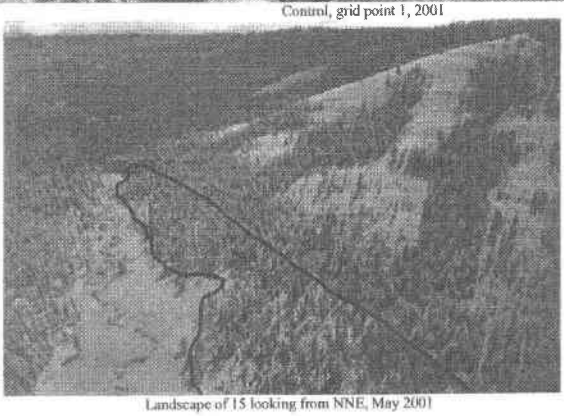
Post treatment, grid point 11, 2001

Landscape of 11 looking from S, May 2001

Figure 74 Unit 15 Control

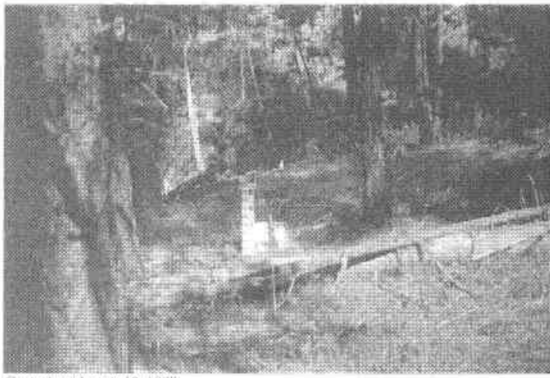
Control, grid point 1, 1998

Control, grid point 1, 2001

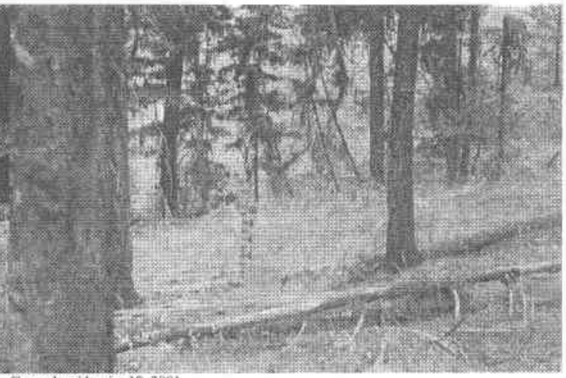


Landscape of 15 looking from NNE, May 2001

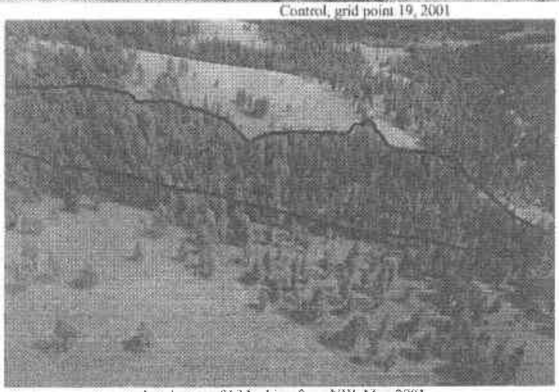
Figure 75 Unit 18 Control



Control, grid point 19, 1998



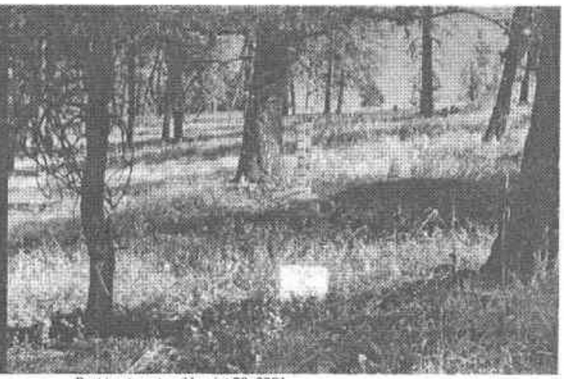
Control, grid point 19, 2001



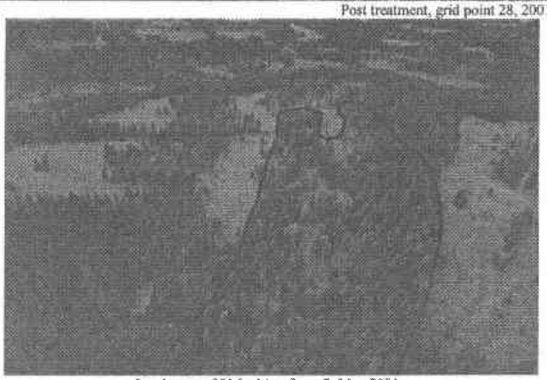
Landscape of 18 looking from NW, May 2001

Figure 76 Unit 21 Burn

Pre treatment, grid point 28, 1998

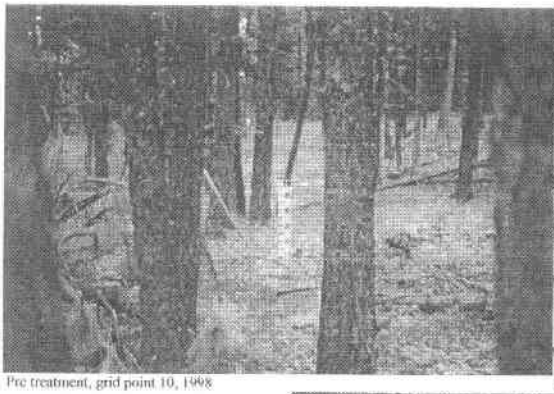


Post treatment, grid point 28, 2001

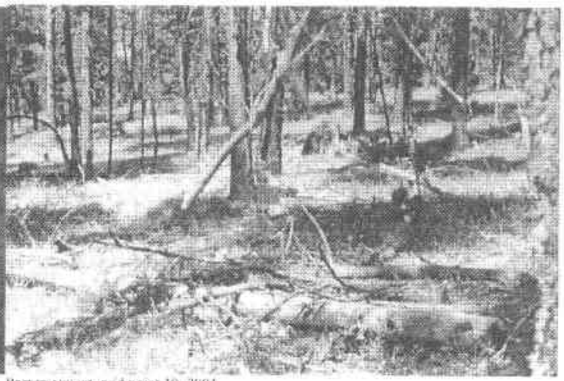


Landscape of 21 looking from S, May 2001

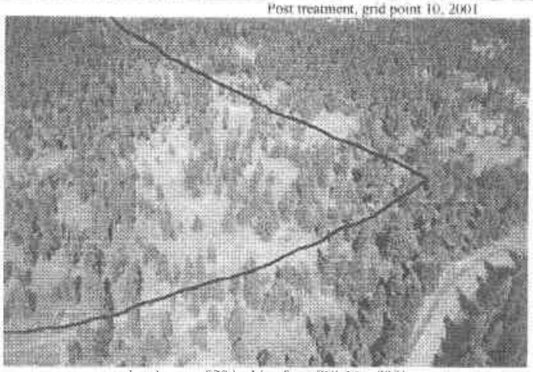
Figure 77 Unit 22 Thin



Pre treatment, grid point 10, 1998



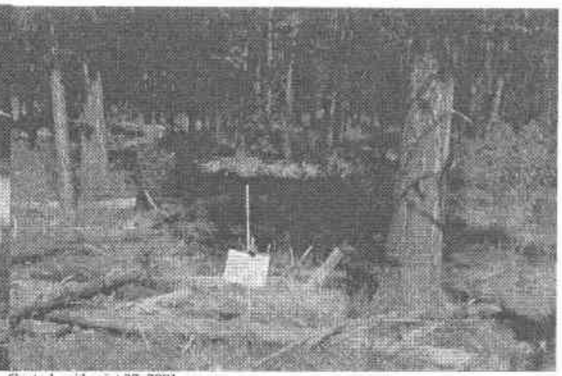
Post treatment, grid point 10, 2001



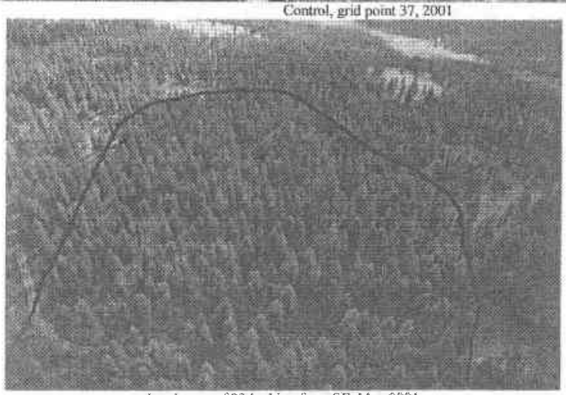
Landscape of 22 looking from SW, May 2001

Figure 78 Unit 23 Control

Control, grid point 37, 1998

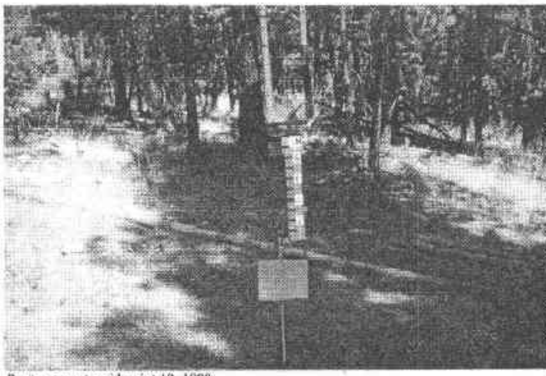


Control, grid point 37, 2001



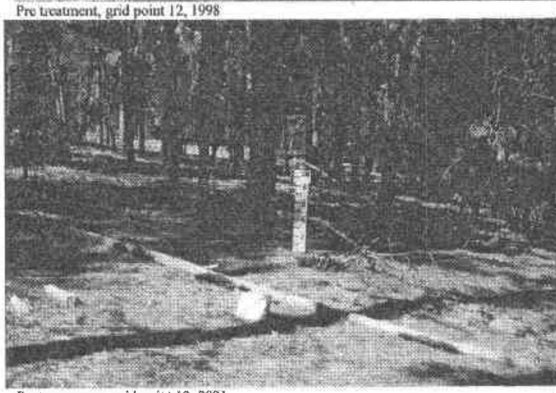
Landscape of 23 looking from SE, May 2001

Figure 79 Unit 24 Burn

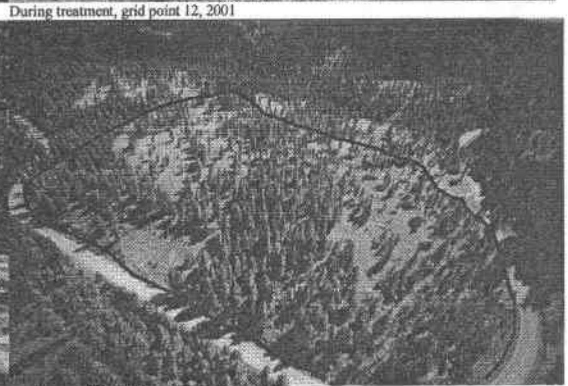


Pre treatment, grid point 12, 1998

During treatment, grid point 12, 2001



Post treatment, grid point 12, 2001



Landscape of 24 looking from N, May 2001

Appendix B PACE Ownership and Operating Cost Equations

Ownership Cost, Equations and Variables:

P = purchase price

S = salvage value

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

N = estimated life of equipment

SH = scheduled hours/year

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

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

1. Straight-line Depreciation ($/year)

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

2. Average Annual Investment ($/year)

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

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

$$I = \% \times AAI$$

4. Ownership Cost ($/hour)

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

Operating Cost: Equations and Variables:

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

d = percent of depreciation for repairs and maintenance

F = fuel consumption (gallons per hour)

f = fuel cost per gallon

L = percent of fuel consumption for oil and lubricants

l = cost of oil and lubricants per gallon

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

s_i = life span of the above item (hours)

1. Repair and Maintenance ($/hour)

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

2. Fuel ($/hour)

$$Fuel = F + f$$

3. Oil and Lubrication ($/hour)

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

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

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

5. Total Operating Cost ($/hour)

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

Labor Cost, Equations and Variables:

TW = total crew or individual wage

FB = percent for fringe benefits

T = travel time per day (hours)

OP = hours worked per day (hour)

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

1. Direct Labor Cost ($/hour)

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

2. Supervision and Overhead ($/hour)

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

3. Total Labor Cost

$$Total\ Labor\ Cost = Direct\ LC + Supervision$$

Appendix C PACE Output

Figure 80 Ownership and operating cost (PACE output) for Rottne harvester.

Equipment Ownership Cost Inputs			
Delivered equipment cost	$	480,000	
Minus line and rigging cost	$	0	
Minus tire and track replacement cost	$	7,000	
Minus residual (salvage) value	$	96,000	
Life of equipment (Years)	#	5	
Number of days worked per year	#	200	
Number of hours worked per day	#	8	
Interest Expense	%	10	
Percent of average annual investment for:			
Taxes, License, Insurance, and Storage	%	3	
Equipment Operating Cost Inputs			
Percent of equipment depreciation for repairs	%	85	
Fuel amount (Gallons per hour)	#	5	
Fuel cost (Per gallon)	$	1	
Percent of fuel consumption for lubricants	%	7	
Cost of oil and lubricants (Per gallon)	$	3.5	
Cost of lines	$	0	
Estimated life of lines (Hours)	#	0	
Cost of rigging	$	0	
Estimated life of rigging (Hours)	#	0	
Cost of tires or tracks	$	7,000	
Estimate life of tires or tracks (Hours)	#	3,200	
Summary			
Ownership			
Depreciable value:	$	377,000	/Year
Equipment depreciation:	$	75,400	/Year
Interest expense:	$	32,640	/Year
Taxes, license, insurance, and storage:	$	9,792	/Year
Annual ownership cost:	$	117,832	/Year
Ownership cost (Subtotal)	$	73.64	/Hour
Machine operating			
Repairs and maintenance:	$	40.1	/Hour
Fuel and oil:	$	6.2	/Hour
Lines and rigging:	$	0	/Hour
Tires or Tracks	$	2.19	/Hour
Equipment operating cost (Subtotal):	$	48.47	/Hour
Labor:			
Direct labor cost:	$	20.25	/Hour
Supervision and overhead:	$	2.03	/Hour
Labor cost (Subtotal):	$	22.27	/Hour
OWNERSHIP COST	$	73.64	/Hour
OPERATING COST	$	48.47	/Hour
LABOR COST	$	22.27	/Hour
Machine rate (Ownership + Operating + Labor)	$	144.39	/Hour

Figure 81 Ownership and operating cost (PACE output) for John Deere harvester.

Equipment Ownership Cost Inputs			
Delivered equipment cost	$	420,000	
Minus line and rigging cost	$	0	
Minus tire and track replacement cost	$	10,000	
Minus residual (salvage) value	$	85,600	
Life of equipment (Years)	#	5	
Number of days worked per year	#	200	
Number of hours worked per day	#	8	
Interest Expense	%	10	
Percent of average annual investment for:			
Taxes, License, Insurance, and Storage	%	3	
Equipment Operating Cost Inputs			
Percent of equipment depreciation for repairs	%	85	
Fuel amount (Gallons per hour)	#	4.5	
Fuel cost (Per gallon)	$	1	
Percent of fuel consumption for lubricants	%	7	
Cost of oil and lubricants (Per gallon)	$	3.5	
Cost of lines	$	0	
Estimated life of lines (Hours)	#	0	
Cost of rigging	$	0	
Estimated life of rigging (Hours)	#	0	
Cost of tires or tracks	$	10,000	
Estimate life of tires or tracks (Hours)	#	4,800	
Summary			
Ownership			
Depreciable value:	$	332,400	/Year
Equipment depreciation:	$	66,480	/Year
Interest expense:	$	29,104	/Year
Taxes, license, insurance, and storage:	$	8,731	/Year
Annual ownership cost:	$	104,315	/Year
Ownership cost (Subtotal)	$	65.20	/Hour
Machine operating			
Repairs and maintenance:	$	35.3	/Hour
Fuel and oil:	$	5.6	/Hour
Lines and rigging:	$	0	/Hour
Tires or Tracks	$	2.08	/Hour
Equipment operating cost (Subtotal):	$	43.00	/Hour
Labor:			
Direct labor cost:	$	20.25	/Hour
Supervision and overhead:	$	2.03	/Hour
Labor cost (Subtotal):	$	22.27	/Hour
OWNERSHIP COST	$	65.20	/Hour
OPERATING COST	$	43.00	/Hour
LABOR COST	$	22.27	/Hour
Machine rate (Ownership + Operating + Labor)	$	130.48	/Hour

Figure 82 Ownership and operating cost (PACE output) for Caterpillar harvester.

Equipment Ownership Cost Inputs		
Delivered equipment cost	$	445,000
Minus line and rigging cost	$	0
Minus tire and track replacement cost	$	12,000
Minus residual (salvage) value	$	89,000
Life of equipment (Years)	#	5
Number of days worked per year	#	200
Number of hours worked per day	#	8
Interest Expense	%	10
Percent of average annual investment for:		
Taxes, License, Insurance, and Storage	%	3
Equipment Operating Cost Inputs		
Percent of equipment depreciation for repairs	%	85
Fuel amount (Gallons per hour)	#	4
Fuel cost (Per gallon)	$	1
Percent of fuel consumption for lubricants	%	7
Cost of oil and lubricants (Per gallon)	$	3.5
Cost of lines	$	0
Estimated life of lines (Hours)	#	0
Cost of rigging	$	0
Estimated life of rigging (Hours)	#	0
Cost of tires or tracks	$	12,000
Estimate life of tires or tracks (Hours)	#	4,800

Summary		
Ownership		
Depreciable value:	$	344,000 /Year
Equipment depreciation:	$	68,800 /Year
Interest expense:	$	30,260 /Year
Taxes, license, insurance, and storage:	$	9,078 /Year
Annual ownership cost:	$	108,138 /Year
Ownership cost (Subtotal)	$	67.59 /Hour
Machine operating		
Repairs and maintenance:	$	36.6 /Hour
Fuel and oil:	$	5.0 /Hour
Lines and rigging:	$	0 /Hour
Tires or Tracks	$	2.5 /Hour
Equipment operating cost (Subtotal):	$	44.03 /Hour
Labor:		
Direct labor cost:	$	20.25 /Hour
Supervision and overhead:	$	2.03 /Hour
Labor cost (Subtotal):	$	22.27 /Hour
OWNERSHIP COST	$	67.59 /Hour
OPERATING COST	$	44.03 /Hour
LABOR COST	$	22.27 /Hour
Machine rate (Ownership + Operating + Labor)	$	133.89 /Hour

Figure 83 Ownership and operating cost (PACE output) for Timbco forwarder.

Equipment Ownership Cost Inputs		
Delivered equipment cost	$	318,000
Minus line and rigging cost	$	0
Minus tire and track replacement cost	$	8,000
Minus residual (salvage) value	$	63,600
Life of equipment (Years)	#	5
Number of days worked per year	#	200
Number of hours worked per day	#	8
Interest Expense	%	10
Percent of average annual investment for:		
Taxes, License, Insurance, and Storage	%	3
Equipment Operating Cost Inputs		
Percent of equipment depreciation for repairs	%	65
Fuel amount (Gallons per hour)	#	6
Fuel cost (Per gallon)	$	1
Percent of fuel consumption for lubricants	%	7
Cost of oil and lubricants (Per gallon)	$	3.5
Cost of lines	$	0
Estimated life of lines (Hours)	#	0
Cost of rigging	$	0
Estimated life of rigging (Hours)	#	0
Cost of tires or tracks	$	8,000
Estimate life of tires or tracks (Hours)	#	3,200
Summary		
Ownership		
Depreciable value:	$	246,400 /Year
Equipment depreciation:	$	49,280 /Year
Interest expense:	$	21,624 /Year
Taxes, license, insurance, and storage:	$	6,487 /Year
Annual ownership cost:	$	77,391 /Year
Ownership cost (Subtotal)	$	48.37 /Hour
Machine operating		
Repairs and maintenance:	$	20.3 /Hour
Fuel and oil:	$	7.5 /Hour
Lines and rigging:	$	0 /Hour
Tires or Tracks	$	2.5 /Hour
Equipment operating cost (Subtotal):	$	29.99 /Hour
Labor:		
Direct labor cost:	$	20.25 /Hour
Supervision and overhead:	$	2.03 /Hour
Labor cost (Subtotal):	$	22.27 /Hour
OWNERSHIP COST	$	48.37 /Hour
OPERATING COST	$	29.99 /Hour
LABOR COST	$	22.27 /Hour
Machine rate (Ownership + Operating + Labor)	$	100.63 /Hour

Figure 84 Ownership and operating cost (PACE output) for Rottne SMV forwarder.

Equipment Ownership Cost Inputs		
Delivered equipment cost	$	350,000
Minus line and rigging cost	$	0
Minus tire and track replacement cost	$	7,000
Minus residual (salvage) value	$	70,000
Life of equipment (Years)	#	5
Number of days worked per year	#	200
Number of hours worked per day	#	8
Interest Expense	%	10
Percent of average annual investment for:		
Taxes, License, Insurance, and Storage	%	3
Equipment Operating Cost Inputs		
Percent of equipment depreciation for repairs	%	65
Fuel amount (Gallons per hour)	#	5
Fuel cost (Per gallon)	$	1
Percent of fuel consumption for lubricants	%	7
Cost of oil and lubricants (Per gallon)	$	3.5
Cost of lines	$	0
Estimated life of lines (Hours)	#	0
Cost of rigging	$	0
Estimated life of rigging (Hours)	#	0
Cost of tires or tracks	$	7,000
Estimate life of tires or tracks (Hours)	#	3,200
Summary		
Ownership		
Depreciable value:	$	273 /Year
Equipment depreciation:	$	546,000 /Year
Interest expense:	$	23,800 /Year
Taxes, license, insurance, and storage:	$	7,140 /Year
Annual ownership cost:	$	85,544 /Year
Ownership cost (Subtotal)	$	53.46 /Hour
Machine operating		
Repairs and maintenance:	$	22.2 /Hour
Fuel and oil:	$	6.2 /Hour
Lines and rigging:	$	0 /Hour
Tires or Tracks	$	2.2 /Hour
Equipment operating cost (Subtotal):	$	30.59 /Hour
Labor:		
Direct labor cost:	$	20.25 /Hour
Supervision and overhead:	$	2.03 /Hour
Labor cost (Subtotal):	$	22.27 /Hour
OWNERSHIP COST	$	53.46 /Hour
OPERATING COST	$	30.59 /Hour
LABOR COST	$	22.27 /Hour
Machine rate (Ownership + Operating + Labor)	$	106.33 /Hour

Figure 85 Ownership and operating cost (PACE output) for Rottne Rapid forwarder.

Equipment Ownership Cost Inputs			
Delivered equipment cost	$	300,000	
Minus line and rigging cost	$	0	
Minus tire and track replacement cost	$	7,000	
Minus residual (salvage) value	$	60,000	
Life of equipment (Years)	#	5	
Number of days worked per year	#	200	
Number of hours worked per day	#	8	
Interest Expense	%	10	
Percent of average annual investment for:			
Taxes, License, Insurance, and Storage	%	3	
Equipment Operating Cost Inputs			
Percent of equipment depreciation for repairs	%	65	
Fuel amount (Gallons per hour)	#	4	
Fuel cost (Per gallon)	$	1	
Percent of fuel consumption for lubricants	%	7	
Cost of oil and lubricants (Per gallon)	$	3.5	
Cost of lines	$	0	
Estimated life of lines (Hours)	#	0	
Cost of rigging	$	0	
Estimated life of rigging (Hours)	#	0	
Cost of tires or tracks	$	7,000	
Estimate life of tires or tracks (Hours)	#	3,200	
Summary			
Ownership			
Depreciable value:	$	233,000	/Year
Equipment depreciation:	$	46,600	/Year
Interest expense:	$	20,400	/Year
Taxes, license, insurance, and storage:	$	6,120	/Year
Annual ownership cost:	$	73,120	/Year
Ownership cost (Subtotal)	$	45.70	/Hour
Machine operating			
Repairs and maintenance:	$	18.9	/Hour
Fuel and oil:	$	5.0	/Hour
Lines and rigging:	$	0	/Hour
Tires or Tracks	$	2.2	/Hour
Equipment operating cost (Subtotal):	$	26.10	/Hour
Labor:			
Direct labor cost:	$	20.25	/Hour
Supervision and overhead:	$	2.03	/Hour
Labor cost (Subtotal):	$	22.27	/Hour
OWNERSHIP COST	$	45.70	/Hour
OPERATING COST	$	26.10	/Hour
LABOR COST	$	22.27	/Hour
Machine rate (Ownership + Operating + Labor)	$	94.07	/Hour

Figure 86 Ownership and operating cost (PACE output) for rubber-tired mobile log loader.

Equipment Ownership Cost Inputs		
Delivered equipment cost	$	250,000
Minus line and rigging cost	$	0
Minus tire and track replacement cost	$	2,000
Minus residual (salvage) value	$	50,000
Life of equipment (Years)	#	5
Number of days worked per year	#	200
Number of hours worked per day	#	10
Interest Expense	%	10
Percent of average annual investment for:		
Taxes, License, Insurance, and Storage	%	3
Equipment Operating Cost Inputs		
Percent of equipment depreciation for repairs	%	65
Fuel amount (Gallons per hour)	#	5
Fuel cost (Per gallon)	$	1
Percent of fuel consumption for lubricants	%	7
Cost of oil and lubricants (Per gallon)	$	3.5
Cost of lines	$	0
Estimated life of lines (Hours)	#	0
Cost of rigging	$	0
Estimated life of rigging (Hours)	#	0
Cost of tires or tracks	$	2,000
Estimate life of tires or tracks (Hours)	#	2,400

Summary		
Ownership		
Depreciable value:	$	198,000 /Year
Equipment depreciation:	$	39,600 /Year
Interest expense:	$	17,000 /Year
Taxes, license, insurance, and storage:	$	5,100 /Year
Annual ownership cost:	$	61,700 /Year
Ownership cost (Subtotal)	$	30.85 /Hour
Machine operating		
Repairs and maintenance:	$	12.9 /Hour
Fuel and oil:	$	6.2 /Hour
Lines and rigging:	$	0 /Hour
Tires or Tracks	$	0.83 /Hour
Equipment operating cost (Subtotal):	$	19.93 /Hour
Labor:		
Direct labor cost:	$	20.25 /Hour
Supervision and overhead:	$	2.03 /Hour
Labor cost (Subtotal):	$	22.27 /Hour
OWNERSHIP COST	$	30.85 /Hour
OPERATING COST	$	19.93 /Hour
LABOR COST	$	22.27 /Hour
Machine rate (Ownership + Operating + Labor)	$	73.05 /Hour

Appendix D Detail Time Study Variables

Dependent variables for the harvester were recorded in hundredths of minutes. Two variables were recorded (move and process).

Travel to the tree (move) was the start of each timed cycle. Move started when the previous stem was finished processing and the machine either moved its position or swung the harvester head and boom to another stem. Time was recorded until the machine grasped the next stem for processing.

Cut and process the tree into log lengths (process) was the time it took for the machine to either cut or pick-up the stem, delimb, and process the stem into segments. Time ended when the machine finished processing and movement to the next stem occurred.

The independent variables recorded for each harvester cycle are defined below along with the units of measurement.

The diameter at the stump was recorded in inches, inside bark. This was a measurement of either the stump or large end for downed material. Two measurements were taken at 90-degree angles and averaged. In cases where standing material was pre measured, the DBH was assumed to be the diameter at the stump, inside bark. This was an appropriate assumption due to the slight swell at the base.

Tree species was noted for each cycle as being either ponderosa pine or Douglas-fir.

Tree position was recorded as either live, standing dead, or downed material. Live trees had to have at least one visible green branch. Standing dead had no green limbs and was positioned at an angle greater than 45 degrees, with respect to the ground or was to be severed from the stump. Downed material was either severed at the base or had no green limbs and was positioned at an angle less than 45 degrees, with respect to the ground.

The distance traveled during the dependent variable move was measured in feet. If no movement of the machine occurred this value was recorded as zero.

Delays were recorded in hundredth of minutes and one of the delay types below was noted.

- Maintenance delays were a classification given to the daily requirements of the machine. Fuelling, lubing, changing of chain, and data download were among the activities recorded as maintenance.
- Mechanical delays were a classification given to non-scheduled and unexpected mechanical breakdowns or technical problems associated with the machine. Dislodging material in the harvesting head and under-carriage, blown or leaking hydraulics, thrown chain, and computer malfunctions were among the actives recorded as mechanical.

- Personal delays were a classification given to the operator and were associated with unscheduled breaks (i.e. lunch was not a personal delay). Radio communications (cell phone use primarily), casual communications with other operators, USDA-Forest Service employees, and researchers, and personal relief breaks were among the activities recorded as personal.
- Other delays were a classification given to any aspect of the operation that did not fall within the above three.

Dependent variables for the forwarder were recorded in hundredths of minutes. Four variables were recorded (travel unloaded, load, travel loaded, and unload).

Travel unloaded defined the beginning of each timed cycle. Time began when the machine had finished unloading and made progress back into the stand. Time stopped when the machine stopped to pick-up the first stem.

Load time was recorded while the machine was stationary and loading stems into the machines bunks. Time started when the machine stopped and ended when movement resumed. This time element occurred multiple times during a cycle.

Travel loaded included all time the machine moved while having at least one log loaded into its bunk. Time started when movement occurred and ended when the machine stopped and began to load. This time element occurred multiple times during a cycle.

Unload was time it took the machine to empty its bunk at a landing. Time started when the machine left the stand and entered a landing area. Time ended when the machine had emptied its load and started to travel back into the stand empty.

The independent variables recorded for each forwarder cycle are defined below along with the units of measurement.

Number of stops to load was measured by counting the times the machine stops to load each cycle.

Number of pulpwood pieces unloaded was measured by counting the pieces of pulpwood material the operator removed from the bunk of the forwarder at the landing. This was delineated by which log deck the operator offloaded material onto.

Number of sawlog pieces unloaded was measured by counting the pieces of sawlog material the operator removed from the bunk of the forwarder at the landing. This was delineated by which log deck the operator offloaded material onto.

Delays were recorded in hundredth of minutes with similar classifications to those of the harvester.

Time elements for the prescribed fire treatments were recorded for a randomly selected crewmember. The variables recorded are defined as follows (100^{th} min.):

- Planning included the preburn meeting and any communication with crew or supervisor with regards to the burn treatment.
- Lighting was defined by the actual ignition by the crewmember being observed. It began when they started to move through the stand, igniting a strip line, and ended when their strip was complete or they halted progress due to another timed element or halted to observe fire behavior.
- Holding occurred when the crewmember observed, moved to a fire line perimeter and controlled the progress of the fire or observed fire line behavior.
- Travel within unit was recorded for the observed crewmember as they worked their way back to start a new line, deliver equipment, or for repositioning.
- Traveling by vehicle to and between units was recorded as the crew moved from their base station to the treatment unit, between treatment units, and back to their station on a given day. It was recorded for actual travel time only.
- Preparing equipment was recorded for the filling of drip torches, water bags and tanks, and unloading and distribution of hand tools. It began and ended at travel within unit.
- Delays were all lumped into one category. The primary delay was waiting for proper weather conditions to start ignition.
- Idle (i.e., personal break, waiting for instructions, and any non-burn activity).

Appendix E Shift Level Forms

Figure 87 Shift level form for single-grip harvesters.

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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Figure 88 Shift level form for forwarders.

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	[ ]	[ ]	[ ]

Comments____

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Figure 89 Shift level time study form for prescribed fire page one of three.

Prescribed Burning Monitoring Report Form

Date: 10/18/00
Start Time: 1400
End Time: 2030

Unit Name / Number: Hungry Bob #10A +10B
Burn Boss: Smergut / Gagen

1. Burn Day Conditions

A. RH min 38 max

B. Temp min max 75

C. Wind Direction NE Avg speed 6 MPH – Gusts to 18 mph

D. Spot Weather Satisfactory? (Y) / N (circle one)

If not, why?

2. Fire Behavior / Intensity
(Discuss flame length, intensity, torching, areas of interest or concern, objectives)

Flame lengths varied 2-4 feet, maintained low intensity burn. Nat. fuel portion good results. Most objectives were met – higher burn intensities occurred in portions of the activity unit.

3. Smoke Dispersal

A. Direction SE

B. Height

C. Comments: Smoke dispersal was good – limited effect of smoke inversion on community areas.

4. Fire Effects; Results
(Describe burn day objectives and results, may include stand mortality, consumption, anticipated results, unit specific objectives, etc.)

Some mortality occurred within the activity unit in areas where slash accumulations were heavy. Large down woody debris was mostly 100% consumed.

Figure 90 Shift level time study form for prescribed fire page two of three.

Rx Burn Cost Report

Burn Name Hungry Bob 10A / 10 B Date 9/18/00 Purpose under burn

Personnel Costs

Name	Position	Base Hours	Rate	Subtotal	OT Hours	Rate	Subtotal	Total
Bill	Burn Boss	8	16.57	132.56	6	24.86	149.16	281.72
Mike	Ign spec	8	13.54	108.32	5	20.31	101.55	209.87
Rob	Holding Boss	8	9.77	78.16	5	14.66	73.30	151.46
Zak	Lighter / Holder	8	9.77	78.16	5	14.66	73.30	151.46
Sean		8	8.71	69.68	5	8.71	43.55	113.23
Joe		8	16.57	132.57	5	24.86	124.30	256.87
Yar		8	10.93	87.44	5	16.40	82.00	169.44
JD		8	12.19	97.52	5	18.29	91.45	188.97
Tim		8	10.93	87.44	5	16.40	82.00	169.44
Monty		8	10.93	87.44	5	16.40	82.00	169.44
Kow		8	8.71	69.68	5	13.07	65.35	135.03
Adom		8	8.71	69.68	5	13.07	65.35	135.03
Nicole		8	12.19	97.52	5	18.29	91.45	188.97
Jeromy		8	9.77	78.14	5	14.66	73.30	151.46

Vehicle Costs

Vehicle #	Cost/Mile	Miles	Total Cost
7219	.23	60	13.80
7220	.23	60	13.80
6484	.32	60	19.20
3920	.46	60	27.60
3204	.23	60	13.80
2477	.58	60	34.80

Supply Costs

Item	Item Cost	Quantity	Total Cost
GAS	1.80	40	72.00

Figure 91 Shift level time study form for prescribed fire page three of three.

Helicopter Costs

Helicopter	Flight Cost	Mileage Cost	Personnel Cost	Helitorch	Mixed Fuel Cost

Contractor Costs

Contractor Name	Item	Total Cost

Personnel Costs	2472.39
Vehicle Costs	123.00
Supplies Cost	72.00
Helicopter Cost	N/A
Contractor Cost	N/A
Total Cost	2667.39

PREPARED BY Mike Gagen DATE 9/19/00