AN ABSTRACT OF THE THESIS OF

Michael A. Hargrave for the degree of Master of Forestry in Forest Engineering presented on June 14, 1985.

Title: Identification of Variables Influencing Residual Stand Damage from Skyline Thinning a Young Western Hemlock-Sitka Spruce Stand

Abstract approved: Dr. Julian Sessions

Western hemlock and Sitka spruce are relatively thin-barked species and susceptible to damage during thinning operations. Damage to the wood allows decay-causing fungi to enter resulting in loss of merchantable volume at the time of final harvest. Cable yarding systems are needed for much of the thinning because most hemlock-spruce stands in the Pacific Northwest are located on steep slopes and fragile soils. It is during these thinning operations that much of the damage occurs. The purpose of this study was to determine the significant harvesting variables affecting residual stand damage due to cable thinning a 30-year-old hemlock-spruce stand.

Detailed stand damage measurements were made during logging on nine skyline units in two study areas in western Oregon. Less detailed damage was measured on 18 other units

to determine differences in damage levels between three different thinning treatments: conventional low intensity thinning, conventional high intensity thinning, and a herringbone (strip) thinning. Twenty-two variables were measured in two categories: harvesting variables and stand damage variables. Total scar area per turn (ft^2/turn) was used as the dependent variable.

As a result of regression analysis, the following variables were found to most significantly influence residual stand damage: number of carriage repositions, log angle, carriage clearance, narrow treatment, rigging slinger, and cutter. An analysis of variance showed mean scar area per acre for the narrow and wide treatments were significantly different from the strip treatment.

Only 12 percent of the residual stand (trees/acre) in the strip treatment were damaged. The narrow and wide treatments experienced much higher levels of 47 and 61 percent, respectively. Conventional thinning treatments experienced extensive damage levels (84.78 ft^2/acre in the narrow treatment and 91.64 ft^2/acre in the wide treatment) compared to the strip treatment (17.57 ft^2/acre). Individual scars ranged in size from 0.02 to 14.00 square feet. Of the total scar area in the detailed units, 66.6 percent was found within 20 feet of the skyline corridor centerline.

Identification of Variables Influencing Residual Stand Damage from Skyline Thinning a Young Western Hemlock-Sitka Spruce Stand

by

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A Paper

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Forestry

Completed June 14, 1985

Commencement June 1986

APPROVED:

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Date thesis is presented June 14, 1985

Typed by Judith Sessions for Michael A. Hargrave

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INTRODUCTION

A major concern of forest managers when thinning young stands in the Pacific Northwest is the amount of residual stand damage that occurs. The potential effects of scarring residual trees include loss of growth, loss of volume and log quality to decay, and in extreme cases, mortality. When young stands consist of western hemlock (Tsuga heterophylla (Raf.) Sarg.) - Sitka spruce (Picea sitchensis (Bong.) Carr.) type, these effects may have economic and future stand management ramifications.

The hemlock-spruce type, as reported by Ruth and Harris (1979), occupies a narrow, 2000-mile long band starting near Coos Bay, Oregon and extending north along the Pacific coast to Prince William Sound, Alaska (Figure 1). Both species are commercially attractive, western hemlock more so than Sitka spruce. Unfortunately, western hemlock and Sitka spruce are relatively thin-barked species and susceptible to damage during thinning operations. Removal of the bark or damage to the wood allows decay-causing fungi to enter resulting in loss of merchantable volume at the time of final harvest. Since most hemlock-spruce stands in the Pacific Northwest are located on steep slopes and

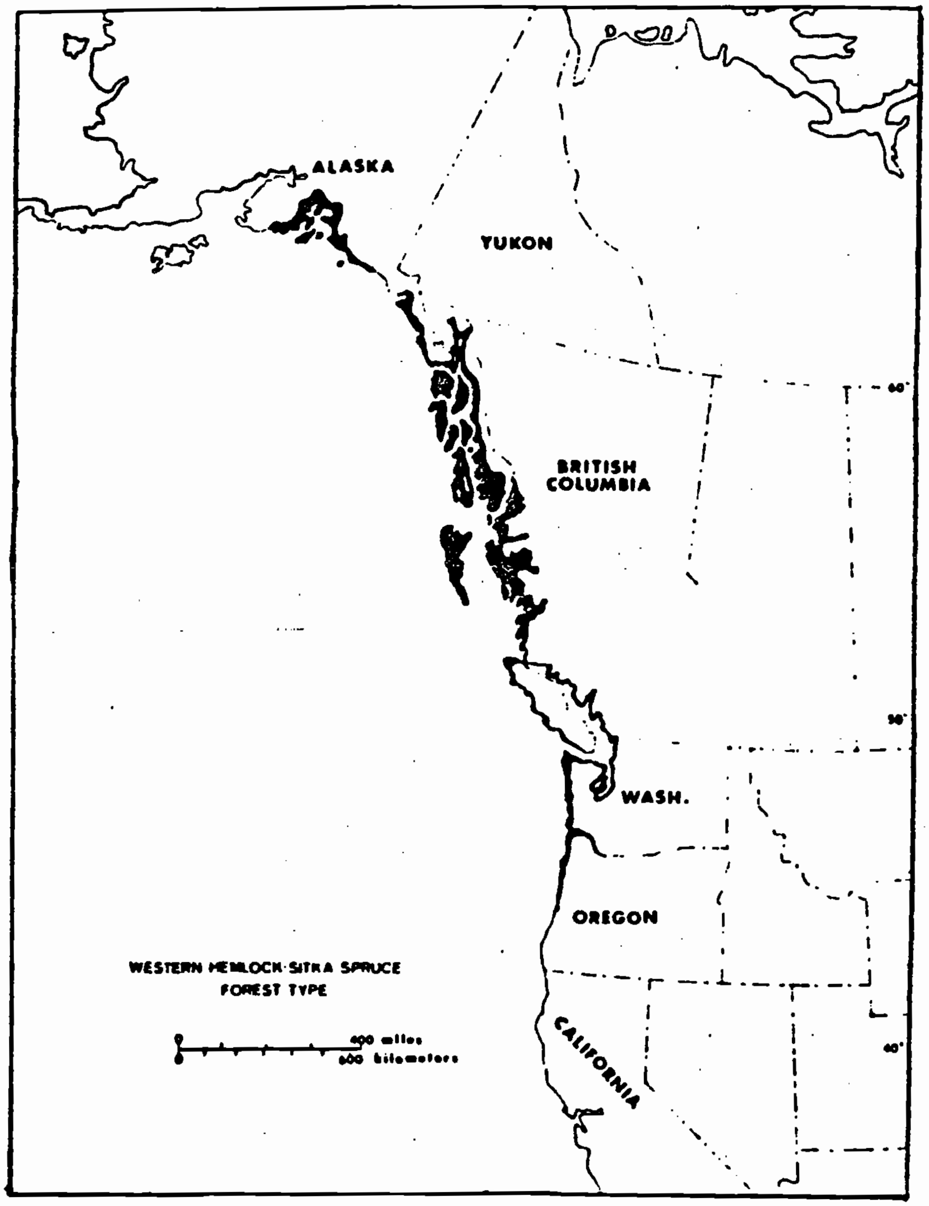


Figure 1. Approximate range of the western hemlock-Sitka spruce forest type.

fragile soils, cable yarding systems are needed for much of the thinning. It is during these thinning operations that much of the damage occurs. To meet objectives of the thinning operation, forest managers must learn how to control the amount of residual stand damage.

SCOPE

This study investigates residual stand damage levels in a young western hemlock-Sitka spruce stand thinned during the summer of 1983. Detailed stand damage measurements were made during logging on nine skyline units to obtain damage characteristics and identify harvesting variables that affected damage. Less detailed damage was measured in the remaining 18 thinning units to determine differences in the level of damage between the three different thinning strategies used in this study.

Regression analysis was used as a tool to determine significant harvesting variables which influence stand damage. The regression model is not intended to be used to predict stand damage. An analysis of variance was conducted to determine if treatments were significantly different. Economics related to future volume losses is not addressed because of a time constraint.

LITERATURE REVIEW

Western hemlock and Sitka spruce are highly susceptible to the root disease, Fomes annosus. Disease spread is by root contact or airborne spores infecting freshly-cut stumps and logging wounds. The invasion of infectious spores leads to a high incidence of decay in logging wounds. However, even though decay incidence is high, future volume losses in short rotation, second growth stands may not be significant. For example, Chavez (1980) found 85 percent of the scars were decayed but only 1.6 percent of the total gross volume was lost due to this decay (Table 1). Wallis, et al. (1971) found small scars (<1 ft^2) are less likely to become decayed (42 %) than large scars (80 %) (Table 2). Parker and Johnson (1960) found 70 percent of spruce butt scars were decayed as opposed to only 38 percent of the scars on the upper bole (Table 3). As height of the logging wound above the ground increases, the frequency of infection decreases significantly (Wright and Isaac, 1956). Therefore, the incidence of decay is related to both scar size and location on the tree. Wallis et al. (1971) reported that decay was confined to wood laid down prior to the time of scarring; therefore, thinning when a stand is young may reduce volume lost to decay in the future.

Past damage studies have identified, either qualitatively or quantitatively, specific logging variables affecting stand damage on a post-logging analysis basis

Table 1. Decay incidence and volume loss as affected by logging damage.

Study	Species	Location	Stand Age	Scar Age	Percent Scars with Decay	Percent Decay of Total Gross Volume
Shea (1961)	DF	SW Wash	114	10	57	1.4
Hunt & Krueger (1962)	DF	W Wash	45	7	13	0.3
Hunt & Krueger (1962)	DF	W Wash	57	6	42	1.2
Wright & Isaac (1956)	WH	W Oreg W Wash	old growth	9-32	63.5	--
Shea (1960)	WH	SW Wash	90	17	55	1.0
Shea (1961)	WH	SW Wash	114	10	92	6.0
Hunt & Krueger (1962)	WH	W Wash	61	6	61	3.4
Wallis et al. (1971)	WH	SW Wash	114	10	92	19.0[2]
Wallis & Morrison (1975)	WH	Coastal B.C.	--	5-25	--	0.5-0.75
Goheen et al. (1980)	WH	W Wash NW Oreg	46-119	10-27	23.1	3.3
Goheen et al. (1980)	WH unthinned	W Wash NW Oreg	46-119	10-27	41.9	2.2[1]
Chavez (1980)	WH	NW Wash	26	11	85	1.6
Wright & Isaac (1956)	True fir	W Oreg W Wash	old growth	9-32	90	--
Shea (1960)	SS	SW Wash	90	17	63	.8
Parker & Johnson (1960)	Spruce	Prince George, B.C.	old growth	15	89	trace[3] 5.8[4]
Parker & Johnson (1960)	Balsam	Prince George, B.C.	old growth	15	89	0.1[3] 5.1[4]
Pawsey & Gladman (1965)	Norway SS	Scotland	60	3-20	?	--

[1] % of merchantable cubic volume
[2] in butt log only over 10 year period
[3] from small scars
[4] from large ground contact scars

Table 2. Decay incidence as affected by scar size.

Study	Species	Scar Size (sq. ft.)	Percent of Scars with Decay
Wallis, Reynolds, & Craig (1971)	WH	<1	42
Wright & Isaac (1956)	WH	<1	48
Wallis, Reynolds, & Craig (1971)	WH	>1	80
Parker & Johnson (1960)	Spruce, Balsam	>1	nearly 100
Wright & Isaac (1956)	WH	>7	100

Table 3. Decay incidence as affected by scar location.

Study	Species	Scar Location	Percent of Scars with decay
Hunt & Krueger (1962)	WH-DF	ground-contact	75
Parker & Johnson (1960)	spruce	butt	70
Shea (1961)	WH	<4.5 ft.	92
Shea (1960)	WH	trunk	91
Shea (1960)	spruce	trunk	88
Parker & Johnson (1960)	spruce	upper bole	38

(Table 4). Obtaining data on specific logging variables during actual harvesting is an important step in developing logging methods and silvicultural prescriptions to minimize residual stand damage and reduce future volume losses. Data is needed in several areas: (1) Identification of variables that influence stand damage during yarding, (2) determination of characteristics of stand damage sustained from the various components of the harvesting operation, (3) control measures for variables that influence stand damage during yarding, and (4) quantification of future stand production losses sustained in a second growth rotation strategy. The objectives for this study were formulated with the above areas in mind.

Table 4. Logging and stand variables influencing stand damage levels.

Study	Species	Location	Stand Age	Yarding Method	Variables: Qualitative	Variables: Quantitative
Aulerich, Johnson, & Froehlich (1974)	DF	W. Oreg.	35	Skyline thinning		Distance from corridor; slope
Gass (1974)	hardwoods larch	Western Russia		Skyline overstory removal	Slope steepness; lateral yarding distance; lead angle; carriage height	
Scherer (1978)	hardwoods DF			Skyline thinning		Distance from corridor
Benson and Gonsior (1981)	DF larch	Montana		Skyline overstory removal	Residual stand density; logging specifications for tree protection; slope; cross-slope; load capacity	
Lysne, Tesch, Helgerson, Brush, and Wearstler (1981)	DF PP	SW. Oreg.	120	Skyline overstory removal	Lead angle; skyline deflection	Skyline corridor cross-slope
Siren (1981)		Finland		Farm tractors, forwarders	Time of year; experience of logger and planner	Strip road width; number of trees cut; residual stand density
Burditt (1981)		Montana Idaho		Skyline thinning		Landing size; tail tree height; # trees cut/acre; # logs/MBF; chordslop
Fieher, Durston, and Varner (1982)	Mixed conifer	N. Calif.	Old growth	Skyline overstory removal		Cross-slope; carriage position; corridor width; carriage clearance
Caccavano (1982)	NW conifers	NW. Oreg.		Skyline thinning		% w. hemlock in residual stand; volume/acre removed; conventional vs. prebunch and swing
Miles and Burk (1984)	Mixed conifer	N. Calif.	Old growth	Skyline thinning	Operator control; machinery operating characteristics; carriage positioning; quality of marking; planning and layout	Log and lead angle; slope

OBJECTIVES

1) Determine the harvesting variables affecting residual stand damage due to cable thinning a young hemlock forest and develop a regression equation to model the relationship.
2) Determine if there is a significant difference in stand damage levels between three different thinning strategies: conventional low intensity thinning, conventional high intensity thinning, and a herringbone thinning.
3) Summarize characteristics of stand damage sustained from logging (number of damaged trees by treatment, scar area, distribution of damaged trees).
4) Recommend logging methods and thinning prescription guidelines that minimize residual stand damage (logging layout, felling pattern, rigging method).

DESCRIPTION OF OVERALL STUDY

Study Area

This study is part of three Cascade Head Experimental Forest research projects areas investigating the management of young hemlock-spruce forests. The research project is a cooperative study involving the following organizations:

- OSU Departments of Forest Engineering, Forest Science, and Forestry Extension Service
- Forest Science Laboratory, Pacific Northwest Forest and Range Experiment Station, Corvallis, Oregon
- Cascade Head Experimental Forest
- Hebo Ranger District, Siuslaw National Forest

For a complete description of the three project areas refer to Appendix A.

The Cascade Head Experimental Forest (Figure 2) is located five miles northeast of Lincoln City, Oregon. Highly productive soils and abundant moisture throughout the year are characteristics of the study site. The timber stand was naturally regenerated, precommercially thinned at age 15 and consisted primarily of 30-year-old western hemlock and Sitka spruce at the time of this study.

The study site was divided into two areas. Area I (Figure 3) was the largest containing 12 compartments and totaling approximately 29 acres. Area II contained 4 compartments on approximately 16 acres (Figure 4).

CASCADE HEAD THINNING STUDY

Vicinity Map

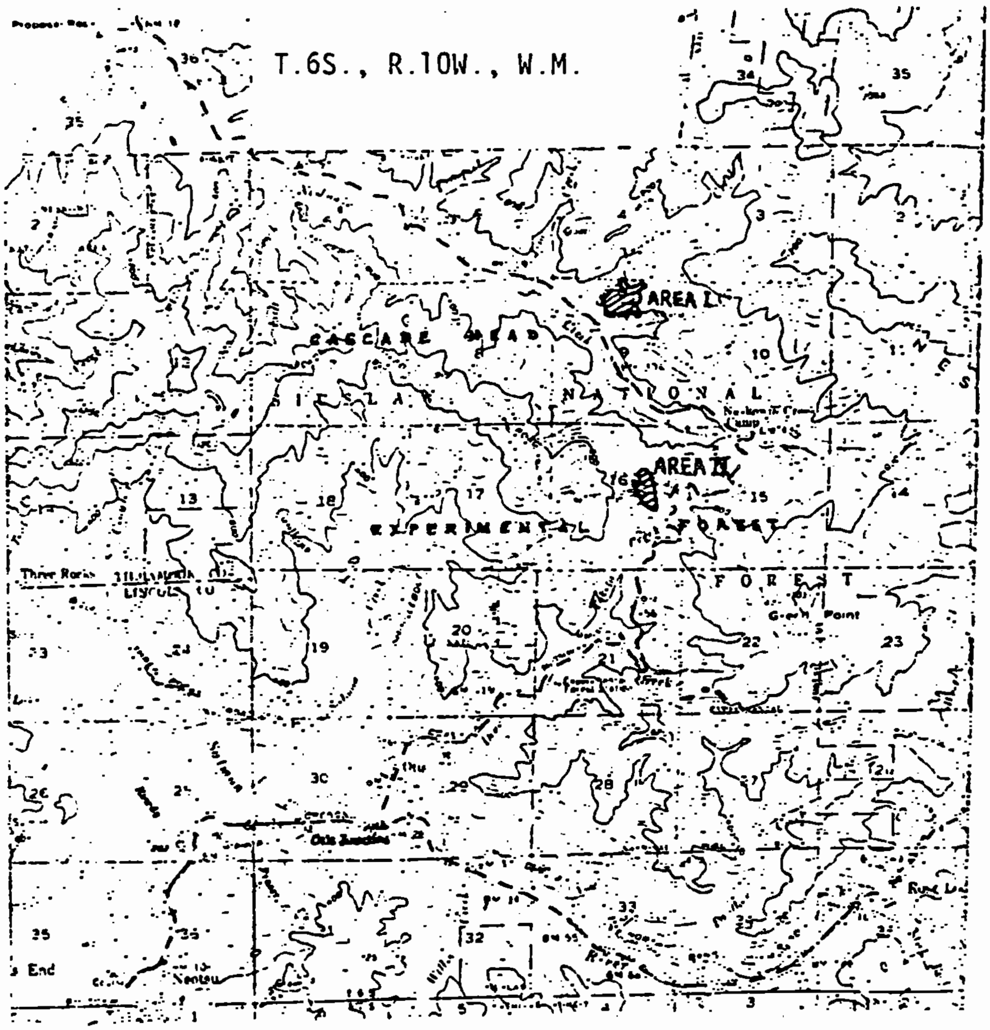


Figure 2. Cascade Head thinning study vicinity map.

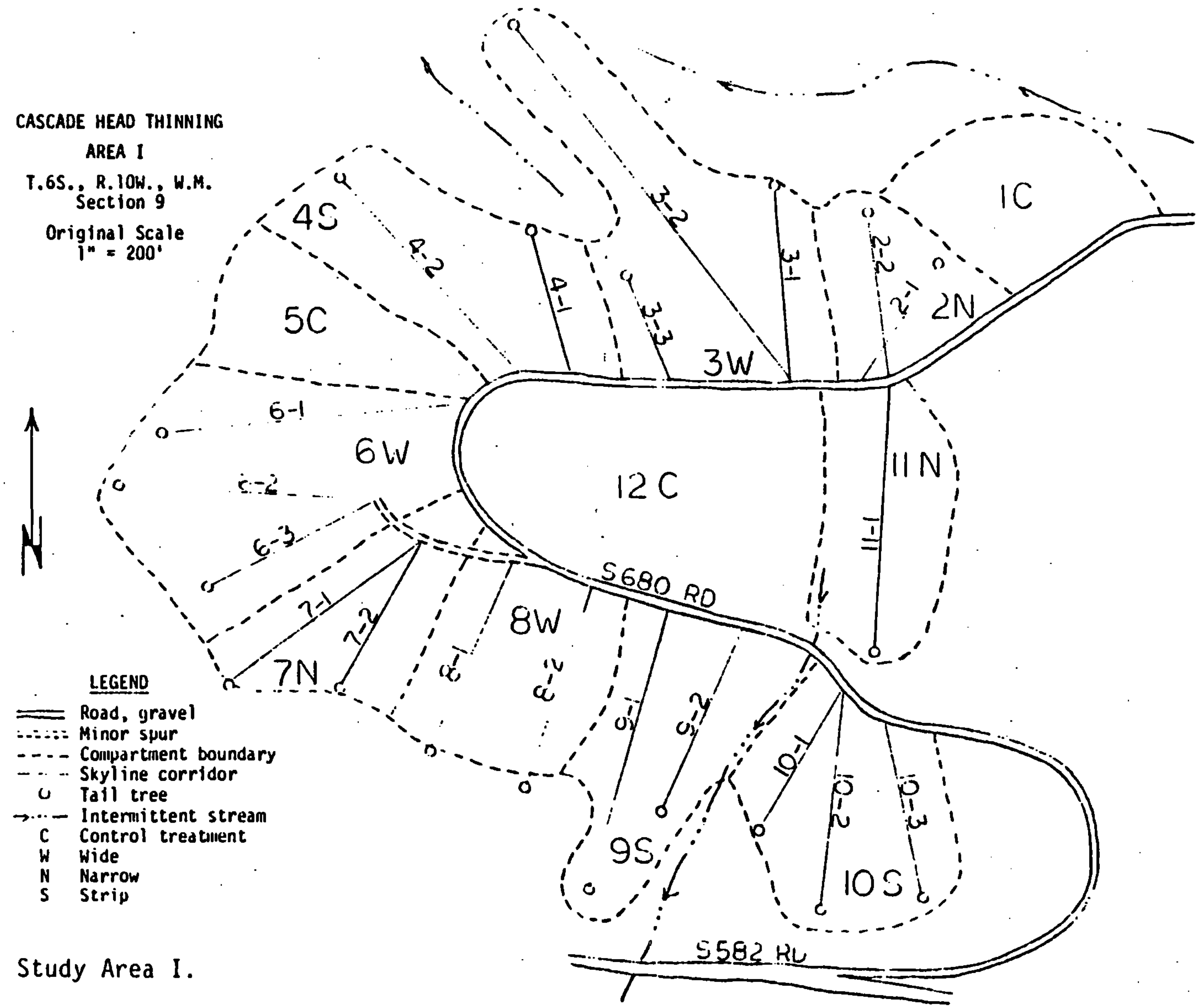


Figure 3. Study Area I.

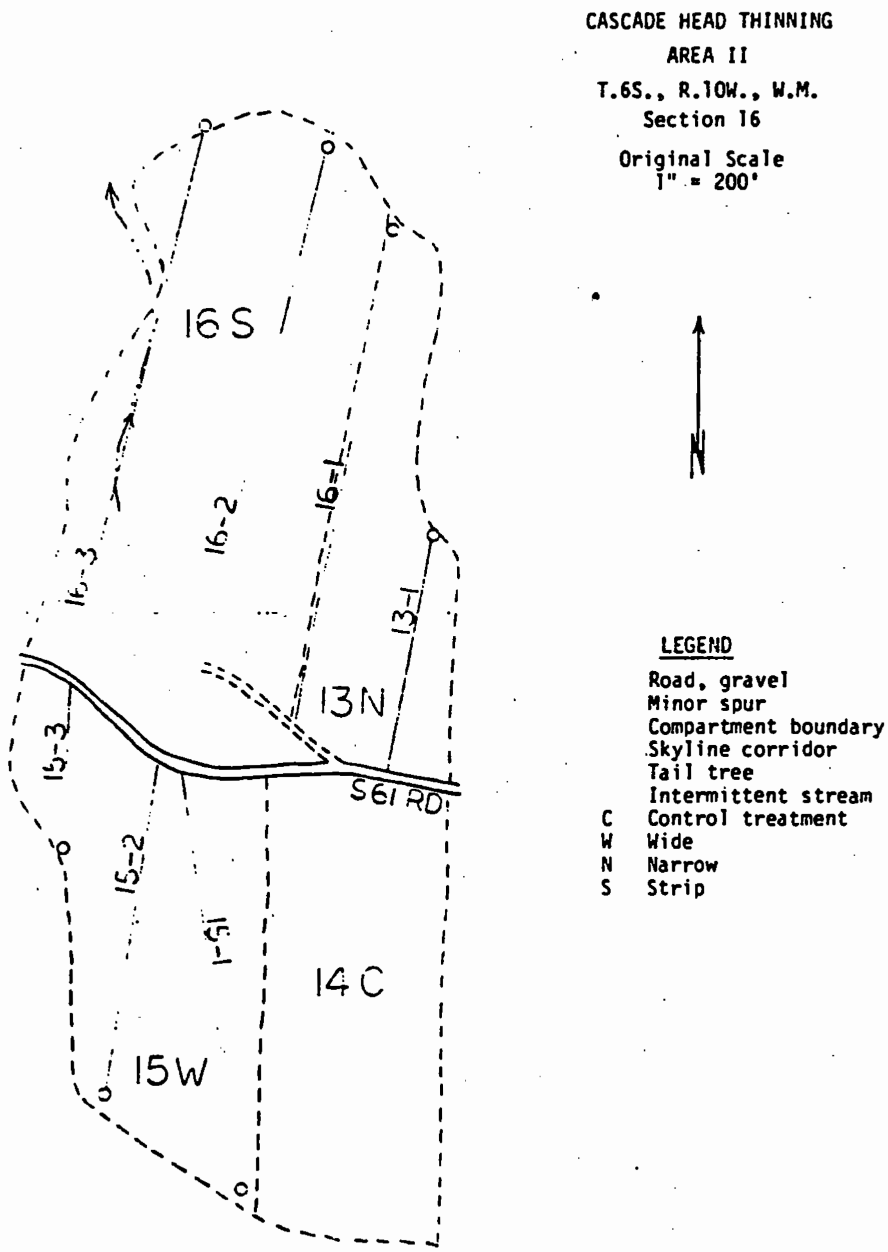


Figure 4. Study Area II.

Compartments were designated by the U.S. Forest Service research group (Greene, 1982). Four silvicultural treatments, also designated by the research group, were replicated four times.

Thinning treatments involved two selection methods resulting in a narrow and a wide spacing of residual trees (Figures 5 and 6). The third treatment, a herringbone design, required twenty-foot-wide lateral cut strips located at a 45 degree angle to the main corridor; thirty-foot-wide leave strips (no thinning) were left between cut strips (Figure 7). The fourth treatment was a control where no thinning took place. Thinning treatments were randomly assigned to each compartment. Compartment layout and tree marking were completed by Siuslaw National Forest sale layout personnel. The narrow and wide treatments were marked leave tree (thinned from below) while the herringbone (strip) treatment was marked take tree.

A detailed timber cruise was conducted after logging using a variable plot program based on the tariff concept (Tappeiner et.al., 1984). Stand data results are summarized in Table 5. Volume removal ranged from 50 to 66 percent for all thinning treatments. Residual species composition were as follows: western hemlock (72% of total trees per acre), Sitka spruce (21%), and Douglas-fir (Pseudotsuga menziesii) (mirb.) Franco] (7%). The average stand diameter at breast height before thinning was 14.8 inches; average total tree

Figure 5. Narrow treatment.

Figure 6. Wide treatment.

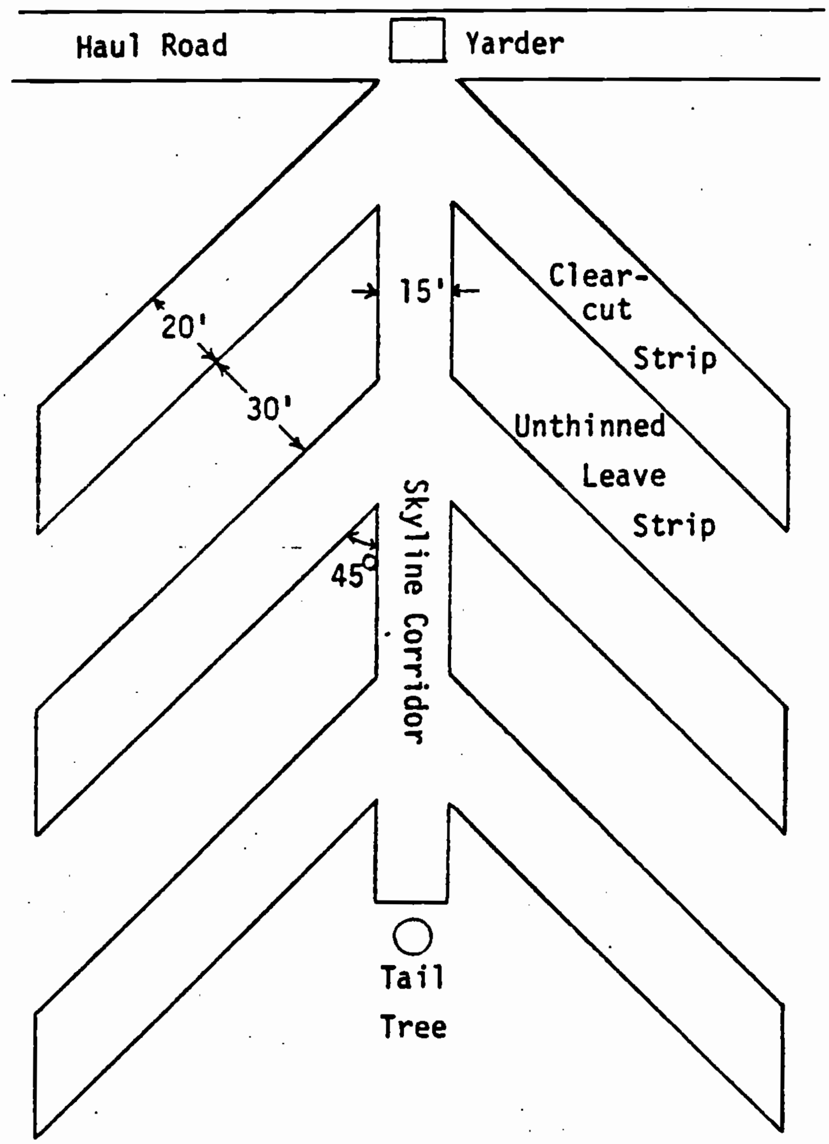


Figure 7. Herringbone thinning pattern.

Table 5. Timber Stand Data.

Treatment	Post Thinning					Thinning Removal			
	Trees per acre	Tree spacing prescribed	Tree spacing actual	Volume/acre ft3	Volume/acre bf	Trees per acre (%)	Basal area per acre (%)	Volume/acre ft3 (%)	Volume/acre bf (%)
Control	208		14.5 x 14.5	6,186	21,032				
Narrow	89	18 x 18	22 x 22	3,069	10,434	119 (57%)	102 (52%)	3,117 (50%)	10,589 (50%)
Wide	67	24 x 24	25.5 x 25.5	2,129	7,239	141 (68%)	132 (67%)	4,057 (66%)	13,793 (66%)
Strip	114			3,024	10,282	94 (49%)	98 (49%)	3,162 (51%)	10,750 (51%)

height was 74 feet. Tree and stand growth rates were as follows: average diameter growth per year was .32 inches, average basal area growth per acre per year was 9.4 square feet, and average volume growth per acre per year was 307 cubic feet.

Logging Layout and Method

The Oregon State University (OSU) Forest Engineering research group planned and layed-out twenty-seven skyline corridors to harvest the thinning treatments on both study areas. Corridors were spaced 150 to 180 feet apart. Span lengths varied from 150 to 750 feet. Unit ground slopes ranged from 0 to 75 percent. Payload analysis was completed for each skyline corridor using an HP-86 desktop computer and the "Logger" program (Nickerson, 1980). Adequate deflection was obtained by taking advantage of the topography for most of the skyline corridors. Tailtrees were required on three corridors and an intermediate support was needed on one.

The logging was contracted out to More Logs, Inc. of Sweet Home, Oregon because of this company's prior thinning experience, appropriate equipment, and anticipated research project cooperation. A Madill 071 mobile yarder and Danebo MSP carriage were used in conjunction with a Bantam C-366 hydraulic heel boom loader (Figures 8 and 9). Yarding equipment specifications are listed in Appendix B. Yarding and loading were accomplished with experienced crew members. The Madill and MSP carriage were rigged in a configuration known as the "Skidder" system with the haulback rigged in the corridor instead of the conventional backline and waistline method (Figure 10). This system permitted fast road changes and problems associated with the closeness of

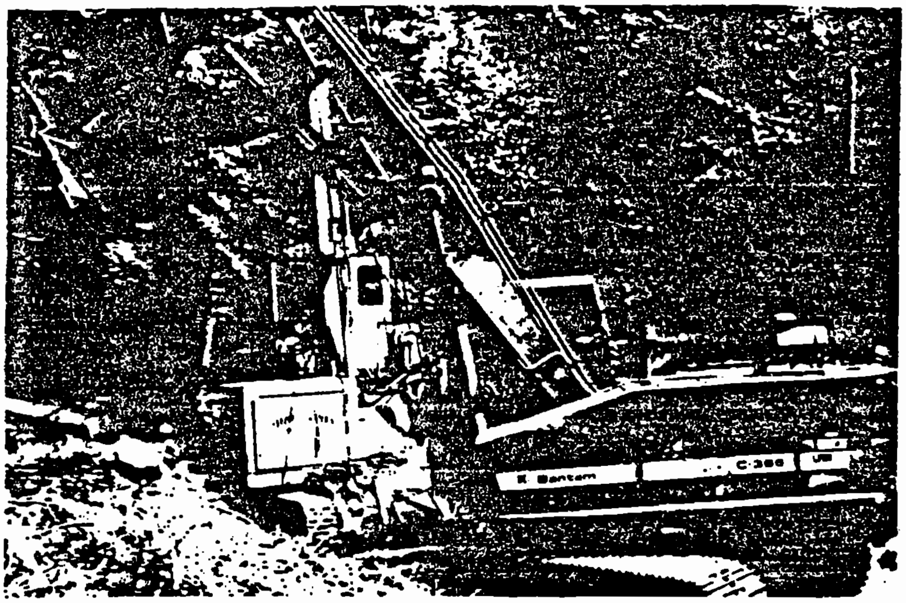


Figure 8. Madill 071 mobile yarder and Bantam C-366 hydraulic heel-boom loader.

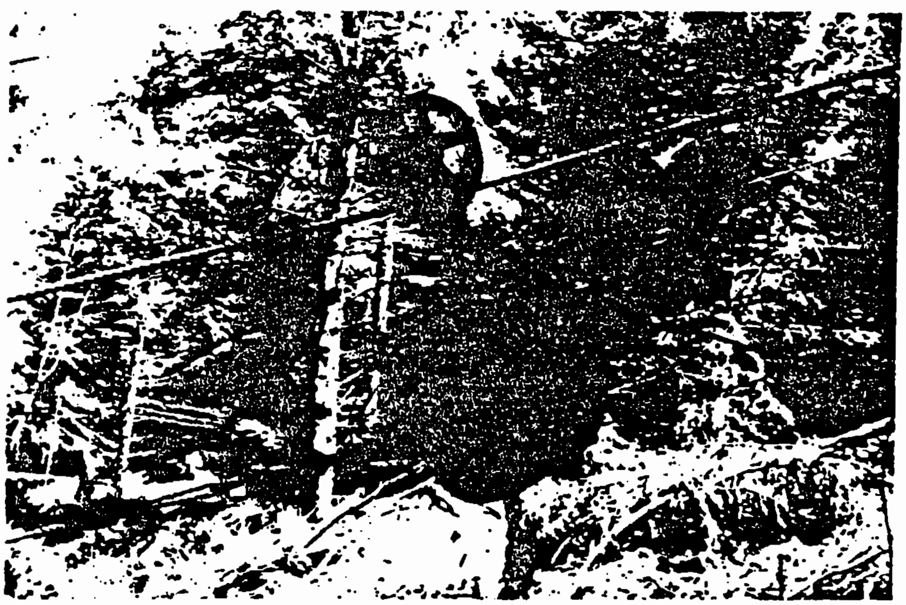


Figure 9. Danebo MSP carriage.

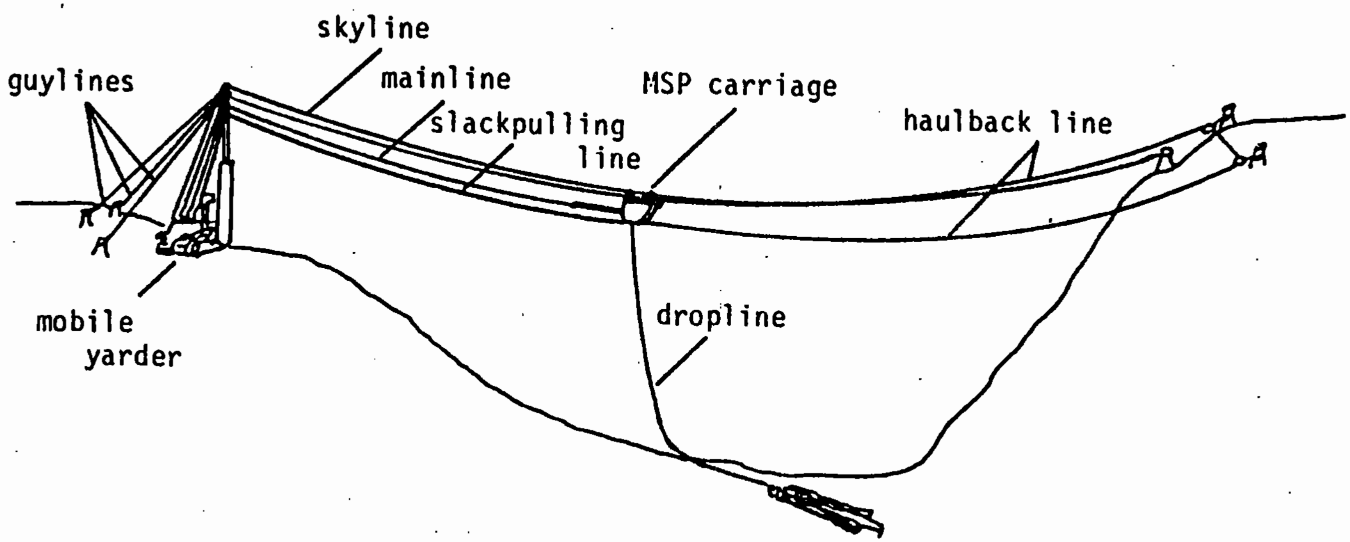


Figure 10. "Skidder" system with MSP carriage.

four lines in the corridor were not encountered. It may also have helped reduce stand damage because the backline of the haulback was not running through the residual stand.

The composition of the crew (total crew size, rigging slinger, loader operator) changed following a one week logging shut down due to uncontrolled circumstances caused by a mill strike and subsequent closure. This change was handled in the study by using appropriate indicator variables.

The felling operation was subcontracted and five cutters completed the work. Cutters were instructed to fall to lead towards the skyline corridor. All cutters were experienced but had varying degrees of ability in felling to lead. Two cutters were studied in detail for the three treatments.

Logs from this study were first hauled to the Fort Hill Lumber mill in Willamina, Oregon. During this mill's forced closure, logs were cold-decked and eventually hauled to Coastal Fibre and Boise Cascade mills in Willamina after yarding had been completed.

STAND DAMAGE STUDY DESIGN

Caccavano (1982) found the distribution of residual stand damage to be highly variable requiring a large sample coverage of a unit to obtain data with significant confidence intervals. For this study, three units were selected in each thinning treatment and detailed stand damage measurements were made during yarding. These units represented the range of yarding conditions present on the site. Criteria used to select these detailed units were based on slope configuration, span length, and chordslope of the skyline (Table 6).

Table 6. Detailed Damage Units.

Unit	Treatment	Slope Configuration	Span Length, ft	Chordslope, %
6-2	wide	concave	460	35
16-1	strip/narrow	concave	720	24
16-2	strip	concave	760	29
8-1	wide	rolling	340	38
9-2	strip	rolling	310	38
13-1	narrow	rolling	450	39
3-1	wide	convex	290	35
4-2	strip	convex	460	39
7-1	narrow	convex	390	34

In addition to the nine detailed damage units, less intensive damage measurements (scar width, length, and area) were made in the remaining 18 units. To account for all damage sustained during the harvest operation, measurements were made at the landing for damage caused by the loader and outside the thinning units for damage caused by the haulback and skyline.

Damage measurements were made only on residual trees whose DBH were ten inches or greater. Trees with DBH less than ten inches were not considered future crop trees by Forest Service standards. Damage types considered were scarring or breakage of the bole due to yarding or felling. Root and branch damage was not measured. Damage sustained from the felling operation was recorded before yarding commenced.

Stand damage characteristics (dependent variable candidates) and influencing variables (independent variables) were measured in detail during and immediately following logging.

Dependent Variable

The dependent variable must be well related to potential losses of volume, growth, or quality. Several characteristics may be used to predict the effect of scarring damage; height of the scar above the ground, width and length of the scar, depth of the scar into the wood, and scar surface area. In previous studies, scar surface area per acre has been used as the dependent variable; Wright and Isaac (1956), Hunt and Krueger (1962), and Caccavano (1982). However, Wallis and Morrison (1975) found wide scars lost twice as much wood to decay as long, narrow scars. Also, deep scars lost a higher percentage of wood than superficial bole injuries. Height of the scar above the ground is another important variable.

This study emphasizes damage differences between three treatments rather than damage differences between many units; therefore, scar area per acre could not be used for detailed analysis (only three measurements exist). Instead, scar area per turn is the dependent variable used for this study. This variable relates the amount of damage which occurred for an individual turn to a set of independent yarding variables characteristic of that turn. In choosing scar area per turn as the dependent variable, a number of independent variables could not be used in the regression analysis; namely, DBH, species, damaged tree position, and slope characteristics. The reason was that a turn of logs could damage more than one tree during lateral inhaul, but only one set of independent variables for only one tree could be regressed against total scar area for that turn.

Independent Harvesting Variables

Independent harvesting variables were measured during the felling and yarding operations for only the nine detailed damage units. Data was recorded on computer-ready coding sheets (Figure 11). Before keypunching, the sheets were reviewed and minor conversions made.

Harvesting variables measured for the regression analysis were as follows:

DETAILED STAND DAMAGE DATA FORM

DATE___/___/___

NAME____________________ CORRIDOR__________

TREATMENT: 18 x 18 ☐
24 x 24 ☐
STRIP ☐

TURN #	SAMPLE I.D.	SP.			DBH	SCAR DAMAGE				DIST DN COR.	DIST FRM COR.	% SL DN	% SL SD	OP		CAUS			LOC			TYPE		DAM WOOD				COMMENTS
		H	S	D		HT	LGTH	WDTH	AREA					Y	F	L	S	C	T	S	C	S	R.B.	1	2	3	4	

Figure 11. Detailed Stand Damage Form.

1) cutter experience: each cutter was interviewed to determine previous thinning experience and subjectively evaluated during the study. The five cutters were then ranked accordingly for the data collection process and data analysis.

2) rigging slinger: each rigging slinger was evaluated on previous thinning experience. A 0-1 indicator variable was used to identify which of the two was working.

3) yarding reset: the number of times the turn of logs was stopped during lateral inhaul in order to reset the chokers.

4) carriage reposition: the number of times the carriage was repositioned during lateral inhaul.

5) logs per turn: the number of logs yarded per turn.

6) volume per turn: prior to yarding, each log was tagged with a number corresponding to diameter and length measurements. As each turn was yarded to the landing, the number was recorded on a form coinciding with that turn. If there was no tag, the log was scaled on the landing.

7) log length: the longest log for each turn.

8) lateral distance: the horizontal distance measured perpendicular from the corridor centerline to the critical log in the turn. The critical log was the log with the probability of causing the most stand damage because of its position (log angle, size, slope).

9) slope distance: the distance measured down the corridor to a point where lateral distance to the critical log was measured from.

10) log angle: see Figure 12.

11) lead angle: see Figure 12.

12) ground clearance: an estimate of the minimum height of the carriage above the ground during lateral yarding.

Stand Damage Variables

Stand damage variables (listed below) were measured for descriptive analysis during yarding and felling for the nine detailed units. The letter (G) means that variable was measured on all 27 units.

1) species (G)

2) DBH (G)

3) scar characteristics: see Figure 13.
   - height
   - length (G)
   - width (G)
   - area (G): the surface area of the scar counting squares on a mesh area gage.
   - depth: penetration of the logging wound into sapwood. Designated by four classes:

     1 - 0-25 percent of the sapwood is partially removed over the scar surface area.
     2 - 26-50 percent
     3 - 51-75 percent
     4 - 76-100 percent

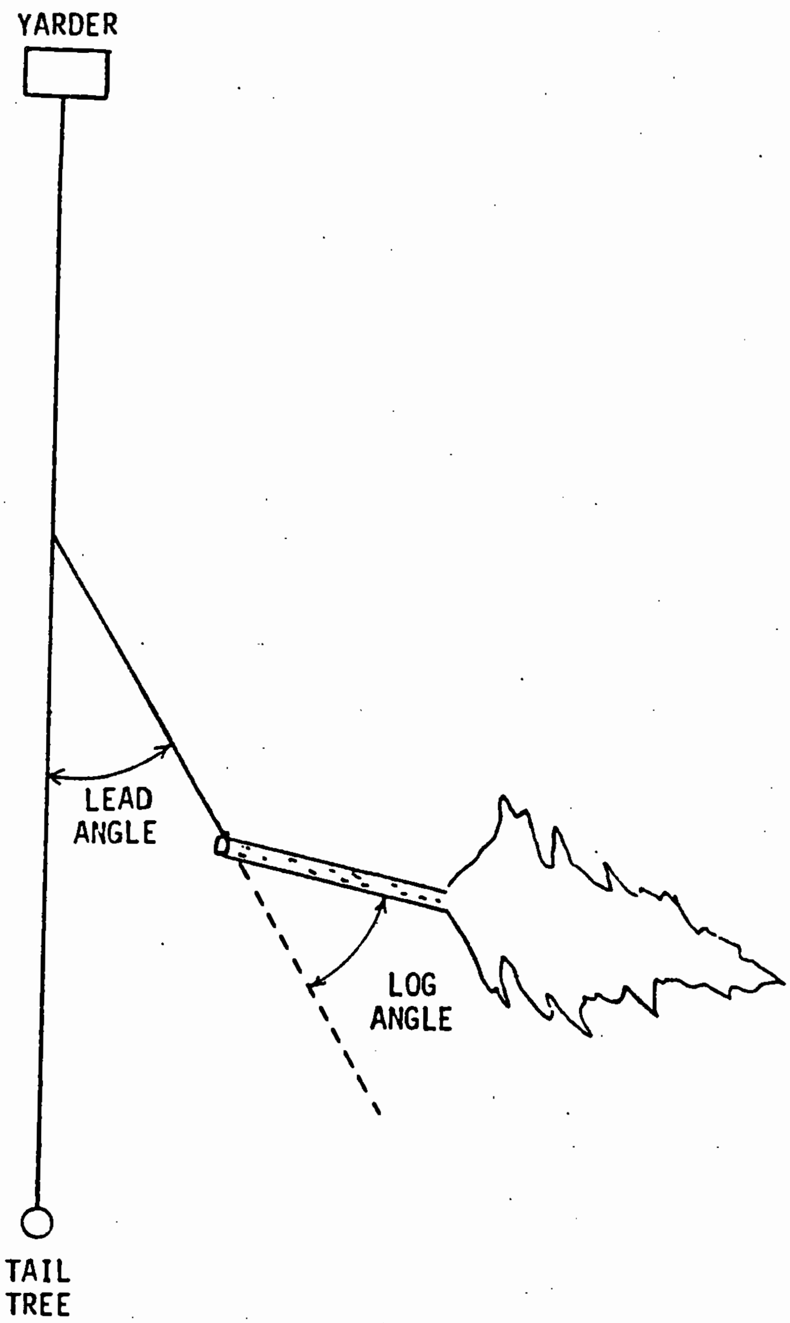


Figure 10. Log and lead angle.

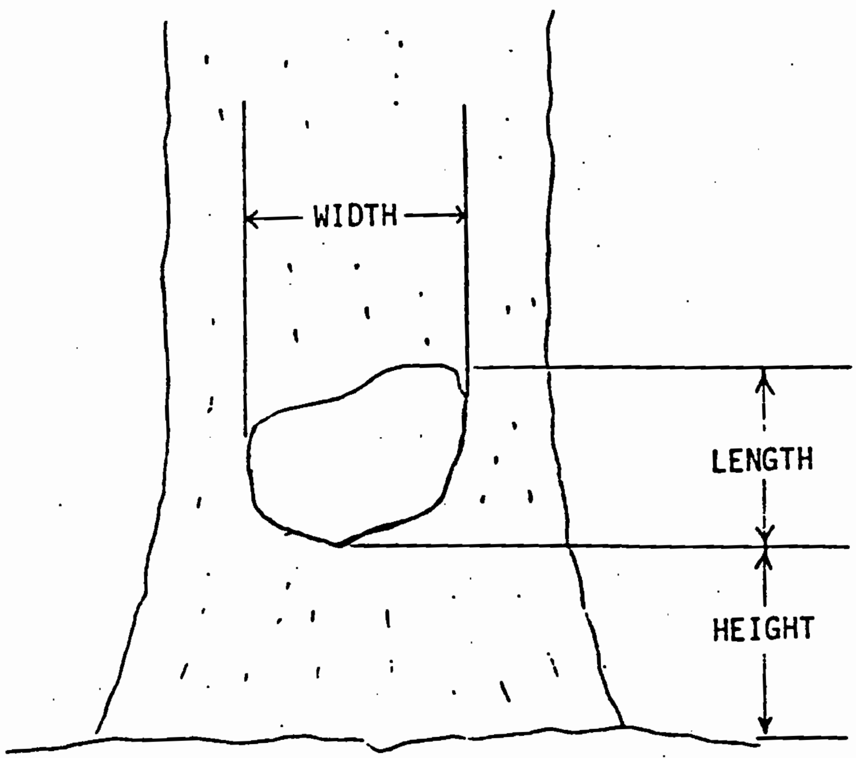


Figure 13. Scar measurements.

Under the appropriate class identifying the damaged sapwood area, a number representing the depth of the wound was recorded. Depth categories are as follows:

1 - the bark was removed but the sapwood was not damaged.
2 - depth of wound was between 0 and 1/4 inch.
3 - depth of wound was 1/4 inch or greater.

4) lateral distance: horizontal distance measured perpendicular from corridor centerline to the damaged tree.

5) slope distance: distance measured down the corridor to the point where lateral distance to the damaged tree was measured from.

6) percent slope downhill: percent slope perpendicular to the contour at the damaged tree.

7) percent slope sidehill: percent slope perpendicular to the corridor at the damaged tree.

8) cause of damage: recorded whether the log, skyline, or carriage was responsible for causing damage.

9) location of damaged tree: recorded whether the tree was located in the thinned area, the strip/leave area, or along the skyline corridor boundary.

10) type of damage: scarred bole, broken top, bent or leaning residual tree.

11) thinning treatment (G).

DATA ANALYSIS

Data analysis was achieved using the Statistical Interactive Programming System (SIPS) on Oregon State University's CYBER 70/73 mainframe computer (Rowe, et.al., 1982). Descriptive statistics were obtained for all independent and dependent variables. Regression analysis was used to build a model incorporating those harvesting variables which influence residual stand damage. The procedure used for building such a model was as follows:

1. To reduce the effects of multicollinearity, intercorrelation was examined between independent variables. If a high correlation exists between two variables (>0.4 for this study), it is difficult to separate their respective effects on the dependent variable. A solution is to drop one of the variables from the analysis. Some of the variables were eliminated at this point.
2. A number of search techniques were used to build the regression model; forward selection, backward selection, and stepwise. The resulting model was in the linear form:

   $$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_n X_n + \epsilon$$
3. A combination of the following criteria was used to evaluate whether the model was the "best":

- coefficient of determination (R^2): the addition of another variable in a search technique failed to increase R^2 more than five percent.
- mean square error of the residuals (MSE): when the MSE decreased to a minimum with the addition of another variable.
- t statistic: only variables significant at the 0.05 probability level or higher were included in the model.
- Cp statistic: the Cp criterion is concerned with the total MSE for the total number of observations for various subset regression models. When there is no bias in the regression model, the expected value of Cp is approximately equal to the number of independent variables in the model. The objective was to identify the subset of variables obtained from the search techniques for which the Cp value is minimum.

4. Residuals from the selected model were analyzed to determine if the following assumptions of the residuals had been met:
   - mean of the residuals is equal to zero
   - residuals are normally distributed about the mean

An analysis of variance was completed to determine if there was a significant difference between the three treatments.

RESULTS

Damage Level Summary

For the nine detailed units, only 12 percent of the residual stand was damaged in the herringbone (strip) treatment (Table 7). The narrow and wide treatments experienced much higher damage levels of 47 and 61 percent, respectively. Diameter distributions are shown in Figures 14-16 which compare damaged trees per acre with residual trees per acre in the detailed units. Note the vertical scale differs for each treatment.

Characteristics of stand damage (scar height, length, width, and area) sustained during the harvesting operation are summarized in Table 8 for all units and treatments. Height of the scar above the ground ranged from a minimum of zero feet at ground level to a maximum of 38 feet. Scar length ranged from 0.10 to 19 feet, scar width from 0.10 to 2.8 feet, and scar area from 0.02 to 14.00 square feet. Figures 17 and 18 are representative of scars measured in the thinning units. In addition to damage measurements taken during yarding, damage (scar area) caused by the felling and loading operations was also measured (Table 9). Only 3.1 percent of the scars measured were caused by the felling operation.

Table 7. Percent residual stand damage by treatment and species.

	Treatment											
	narrow				wide				strip			
		species				species				species		
	Total	WH	SS	DF	Total	WH	SS	DF	Total	WH	SS	DF
Residual Stand (trees/ac)	89	72	6	11	67	57	7	3	114	60	39	15
Stand Damaged (trees/ac)	42	36	2	3	43	33	5	0	14	7	3	2
Stand Damaged (percent)	47	50	33	27	61	58	71	0	12	12	8	13

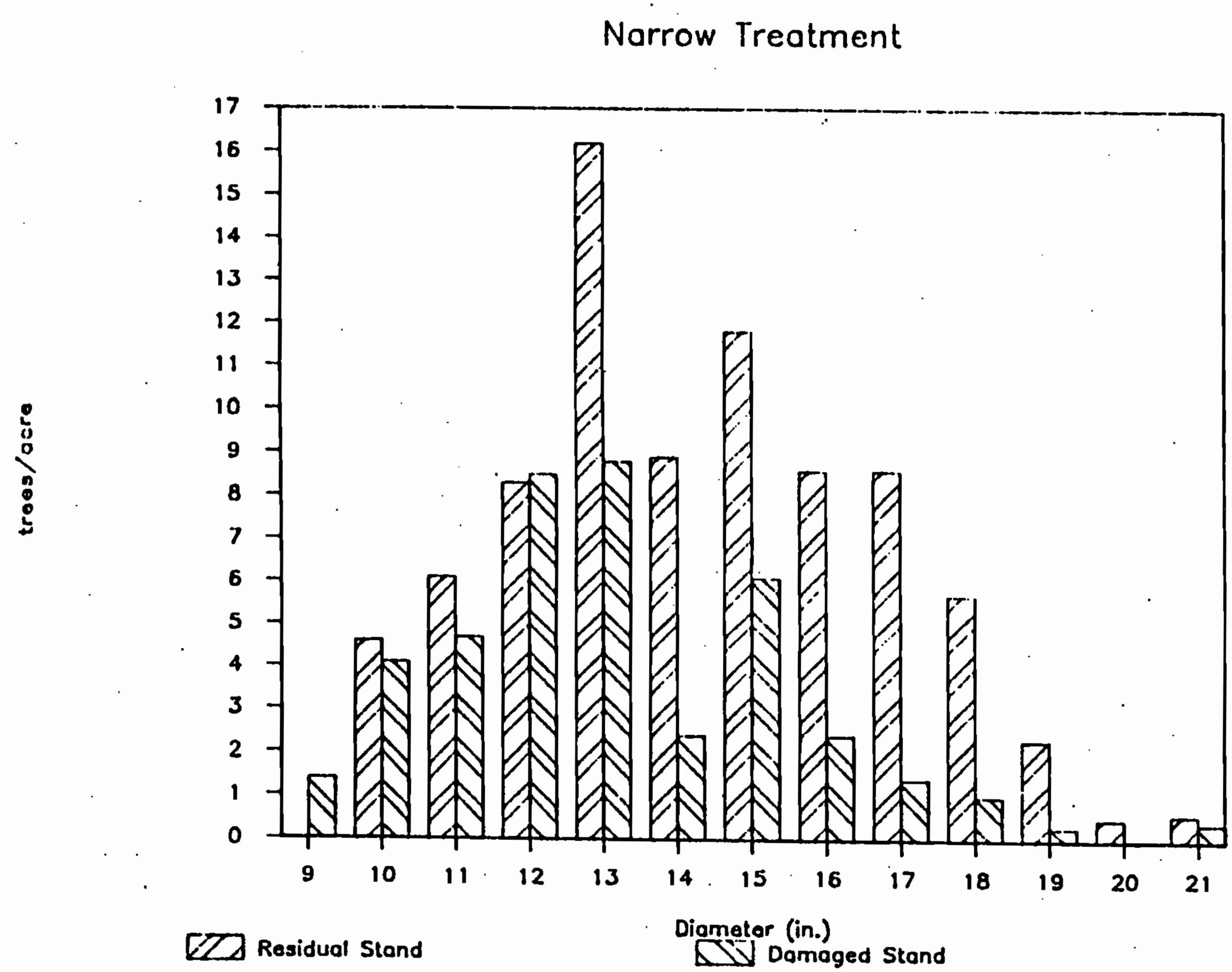


Figure 14. Diameter distribution of residual and damaged trees; narrow treatment.

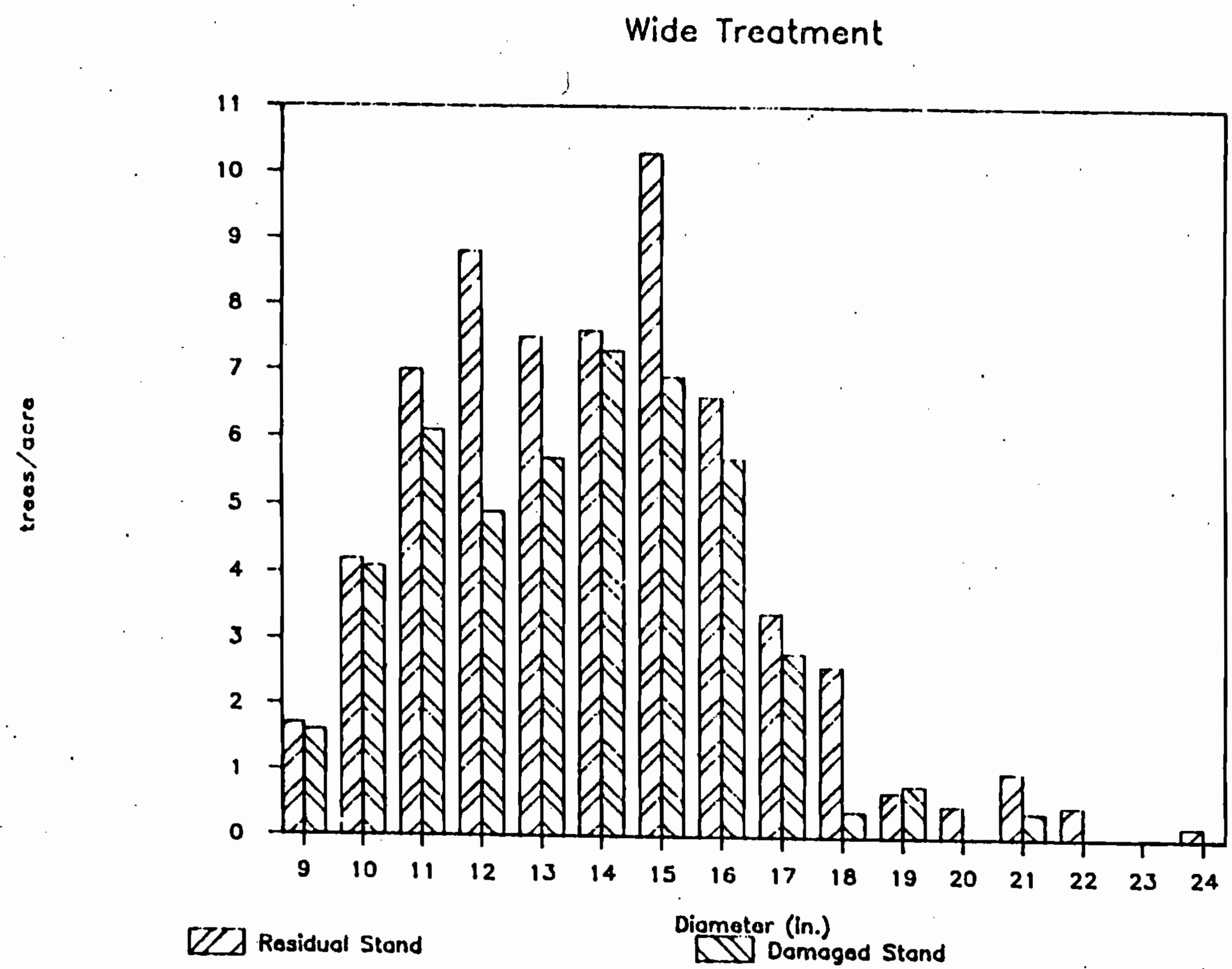


Figure 15. Diameter distribution of residual and damaged trees; wide treatment.

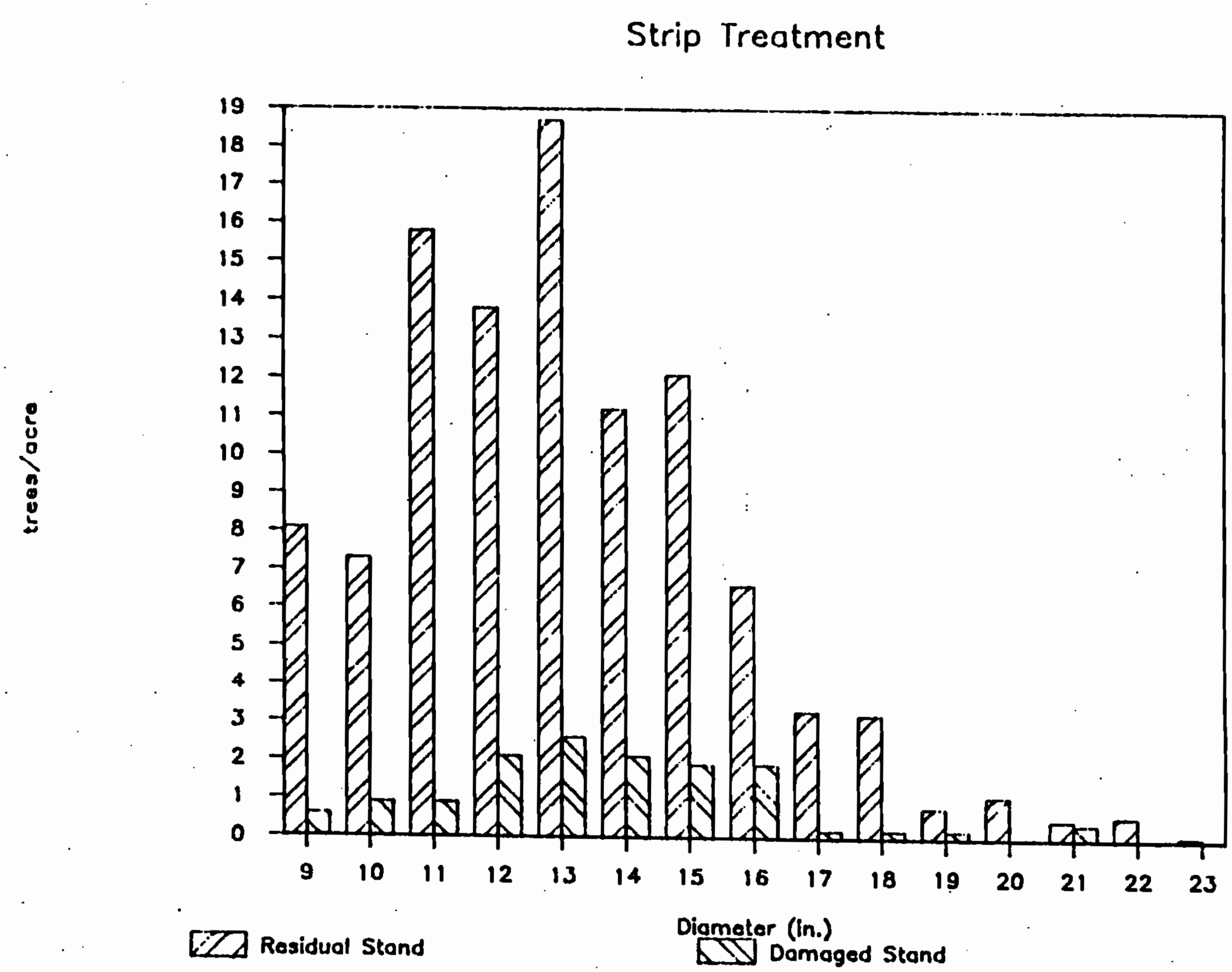


Figure 16. Diameter distribution of residual and damaged trees; strip treatment.

Table 8. Scar characteristics for detailed and gross damage units.

Operation	Treatment	Statistic	Scar Characteristics Height (ft)	Length (ft)	Width (ft)	Area (ft^2)
yarding	all	max	38.00	19.00	2.80	14.00
		mean	4.51	1.37	0.38	0.57
		min	0.00	0.10	0.10	0.02
		stand dev	4.93	1.67	0.27	1.04
		number of scars	1109	2054	2053	2054
	narrow	max	24.00	15.00	2.10	13.01
		mean	4.08	1.47	0.40	0.65
		min	0.00	0.10	0.10	0.02
		stand dev	4.20	1.81	0.27	1.20
		number of scars	451	678	678	678
	wide	max	30.00	14.00	2.30	14.00
		mean	4.58	1.28	0.37	0.51
		min	0.00	0.10	0.10	0.02
		stand dev	4.78	1.41	0.27	0.92
		number of scars	438	934	934	934
	strip	max	38.00	12.00	2.80	9.10
		mean	4.69	1.29	0.36	0.50
		min	0.00	0.10	0.10	0.02
		stand dev	5.88	1.50	0.27	0.84
		number of scars	164	386	385	386

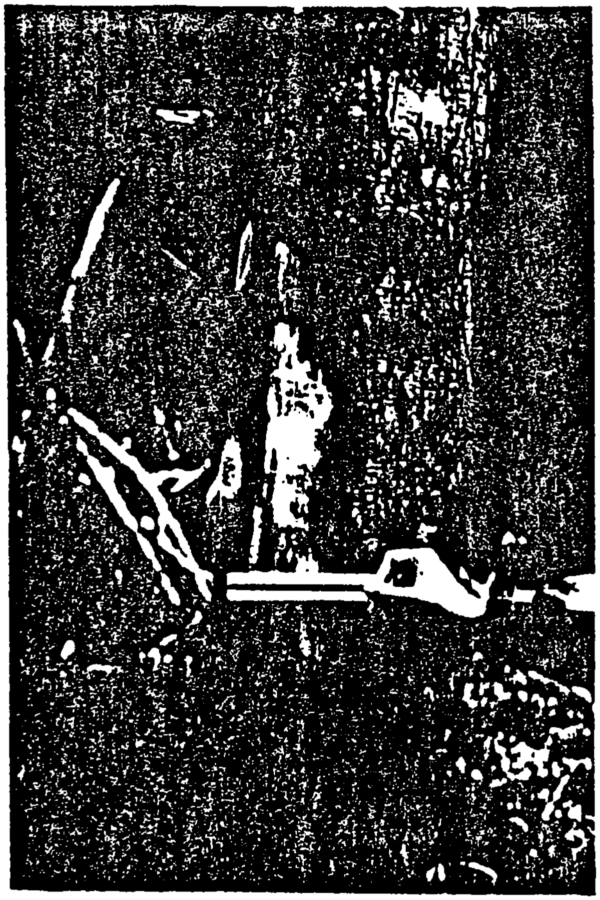


Figure 17. Width of yarding scar measured.

Figure 18. Long, narrow yarding scar and tree identification number.

Table 9. Individual scar area statistics for felling, loading, and outside the thinning unit.

Statistic	Felling	Loading	Outside*
max	3.92	6.55	16.40
mean	0.32	0.38	0.68
min	0.02	0.02	0.02
stand dev		0.68	1.74
number of scars	76	193	13

* For many of the thinning units, the tail and haulback blocks were rigged outside the unit boundary. Damage caused by yarding lines running to these blocks was categorized as "outside" damage.

scar type

Four categories were used to describe the cause of scarring during the yarding operation: log, skyline, log-skidding line combination, and log-skyline-carriage combination (Table 10). For all treatments, 84.3 percent of the scars were caused by a turn of logs. Only 7.7 percent of the scars were caused by the skyline. The skyline corridor was resurveyed after a unit was logged to measure scars not accounted for during yarding. It was difficult to differentiate a skyline scar from a log scar; therefore, the number of log scars may be overestimated and skyline scars underestimated.

Table 10. Cause of scarring.

Cause of scar	All Treatments		Treatment Narrow		Treatment Wide		Treatment Strip	
	scars	%	scars	%	scars	%	scars	%
log	788	(84.3)	318	(88.8)	331	(80.5)	139	(83.7)
skyline	72	(7.7)	29	(8.1)	31	(7.5)	12	(7.2)
log-skidding line	72	(7.7)	10	(2.8)	47	(11.4)	15	(9.0)
log-carriage-skyline	3	(0.3)	1	(0.3)	2	(0.5)	--	
total	935	(100)	358	(100)	411	(100)	166	(100)

scar location

Scars were also classified into three location categories: within the residual stand (thin), along the edge of a leave strip (strip), or along the corridor edge (corridor). For all treatments, 52.2 percent of the scars were located at the edge of a corridor and 39.1 percent within the residual stand (Table 11).

Table 11. Location of scars.

Scar Location	All Treatments scars %	Treatment Narrow scars %	Treatment Wide scars %	Treatment Strip scars %
thin	366 (39.1)	152 (42.5)	214 (52.1)	--
strip	81 (8.7)	--	--	81 (48.9)
corridor	488 (52.2)	206 (57.5)	197 (47.9)	85 (51.2)
total	935 (100)	358 (100)	411 (100)	166 (100)

scar depth

Four classes were used to designate the amount of sapwood removed over the scar surface area for each logging wound. Class 1 meant 0-25 percent of the sapwood was removed; classes 2, 3, and 4 meant 26-50, 51-75, and 76-100 percent was removed, respectively. Under the appropriate class identifying the damaged sapwood area, a number representing the depth of the wound was listed. Three depth classes were used: class 1 meant the bark was removed but the sapwood was not damaged; class 2 meant the depth of the wound was less than or equal to 1/4 inch; and class 3 was used for all wounds deeper than 1/4 inch. For example, a scar with just the bark removed was listed under sapwood class 1 and depth class 1. Most of the scars (63.2 %) fell into this category. If the scar was 1/8 inch deep over 40 percent of the scar surface area, it was listed under sapwood class 2 and depth class 2. Very few scars (0.9 %) fell into this category. Table 12 summarizes sapwood damage and scar depth for all treatments.

scar height

Out of 973 scars, 23.2 percent were located within one foot of the ground, 59.2 percent between one and seven feet, and 17.6 percent over seven feet for all treatments (Table 13). A chi-square test for independence was conducted to test the hypothesis that thinning treatment had no effect on height of the scar above the ground. The observed value of $\chi^2 = 15.83$. For four degrees of freedom, the probability that $\chi^2 > 15.83 = 0.005$. In other words, if treatment and scar height are independent, a value larger than the observed value of χ^2 can occur less than five times in 1000. Therefore, the hypothesis is rejected and conclude that thinning treatment and height of scar above the ground are related.

Table 12. Frequency (%) of scars in sapwood damage and depth classes.

Treatment	Wound Depth Class	Sapwood Damage Class 1	2	3	4	Total
all	1	63.2	--	--	--	63.2
	2	16.6	0.9	1.1	10.4	29.0
	3	5.5	1.0	0.5	0.8	7.8
	Total	85.2	2.0	1.6	11.2	100.0
narrow	1	77.2	--	--	--	77.2
	2	17.3	0.3	0.8	--	18.4
	3	3.6	--	0.8	--	4.4
	Total	98.1	0.3	1.6	--	100.0
wide	1	52.0	--	--	--	52.0
	2	13.6	0.9	1.6	19.2	35.3
	3	8.1	2.3	0.5	1.8	12.7
	Total	73.7	3.2	2.1	21.0	100.0
strip	1	62.8	--	--	--	62.8
	2	22.7	2.3	0.6	9.3	34.9
	3	2.3	--	--	--	2.3
	Total	87.8	2.3	0.6	9.3	100.0

Table 13. Frequency of scars in height categories.

Scar Height	All Treatments scars %	Narrow scars %	Treatment Wide scars %	Strip scars %
< 1.0 ft	226 (23.2)	82 (20.7)	94 (22.7)	50 (30.7)
1.1-7.0 ft	576 (59.2)	258 (65.2)	240 (60.0)	78 (47.8)
> 7.1 ft	171 (17.6)	56 (14.1)	80 (19.3)	35 (21.5)
total	973 (100)	396 (100)	414 (100)	163 (100)

corridor width

The skyline corridors were felled to a width of 10-15 feet. During the yarding, a number of corridor boundary trees were felled because they were pulled over or badly damaged during yarding. Upon completion of yarding, the widths of the corridor were measured to compare with the corridor measurements before yarding (Table 14). One reason why corridor widths increased was because the skyline was not always rigged down the center of the corridor (Figure 19). This was the case for units 3-1 and 6-2. When a turn was yarded to the corridor, and the skyline was skewed towards that side of the corridor, the chances of pulling over a corridor tree were observed to have greatly increased. Another reason for increased corridor widths was improper lead of the felled timber and improper carriage positioning creating an undesirable lead angle.

Table 14. Corridor widths and number of trees felled for all detailed units.

Unit	Average Width After Thinning	Damaged or Pulled Over Corridor Tree which were Felled
13-1	15	4
16-1	15	3
16-2	24	1
3-1	31	1
4-2	19	1
6-2	31	5
7-1	20	0
8-1	22	5
9-2	20	0

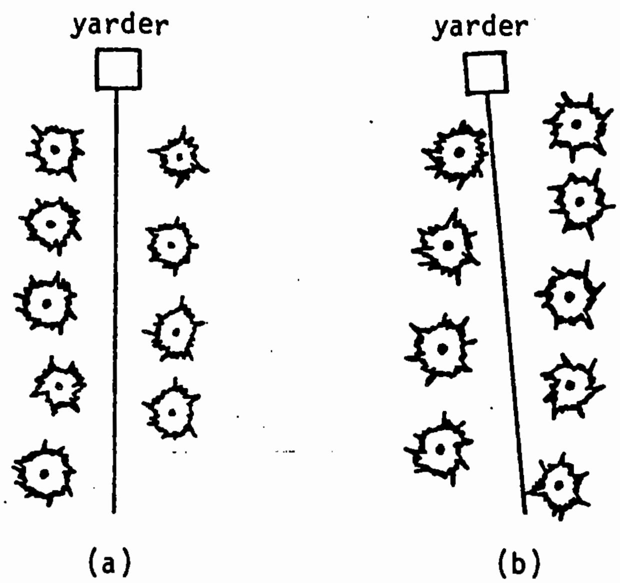


Figure 19. Skyline rigged, (a) correctly and (b) skewed.

damaged tree distributions

Caccavano (1982) found most residual stand damage occurs near the skyline corridor. My study confirms this with 66.6 percent of the total scar area occurring within 20 feet of the skyline corridor centerline (Table 15). Figure 20 is a histogram of total scar area versus lateral yarding distance from the corridor centerline. Lateral distance did not enter the regression model even though Figure 20 apparently shows a relationship exits.

The distribution of damaged trees vary between treatments. The location of each damaged tree in Unit 16-1 is plotted in Figure 21. Unit 16-1 illustrates the difference between the narrow and strip treatments. Most of the damage in the strip treatment occurs as the turn of logs are yarded into the skyline corridor. The turn pivots around a "rub" tree which prevents damage to other trees in the leave strip (Figure 22 and 23). In the narrow and wide treatments, corridor boundary trees may act as potential rub trees depending on the position of the carriage as turns are yarded from the unit. Consequently, a great deal of damage occurs along the corridor edge. Damage can be minimized if the carriage is properly positioned by the rigging slinger creating a satisfactory lead angle.

Table 15. Distribution of scar area within the unit.

Unit	Scar Area < 20 ft from Corridor Centerline (ft^2)	(%)	Total Scar Area in Unit (ft^2)
13-1	57.12	(70.0)	81.62
16-1	117.73	(69.2)	170.11
16-2	24.73	(79.1)	31.27
3-1	33.98	(63.6)	54.41
4-2	34.05	(77.2)	44.11
6-2	15.62	(62.9)	24.82
7-1	45.50	(77.9)	58.40
8-1	77.04	(53.0)	145.35
9-2	.04	(20.0)	.20
Total	405.80	(66.6)	610.29

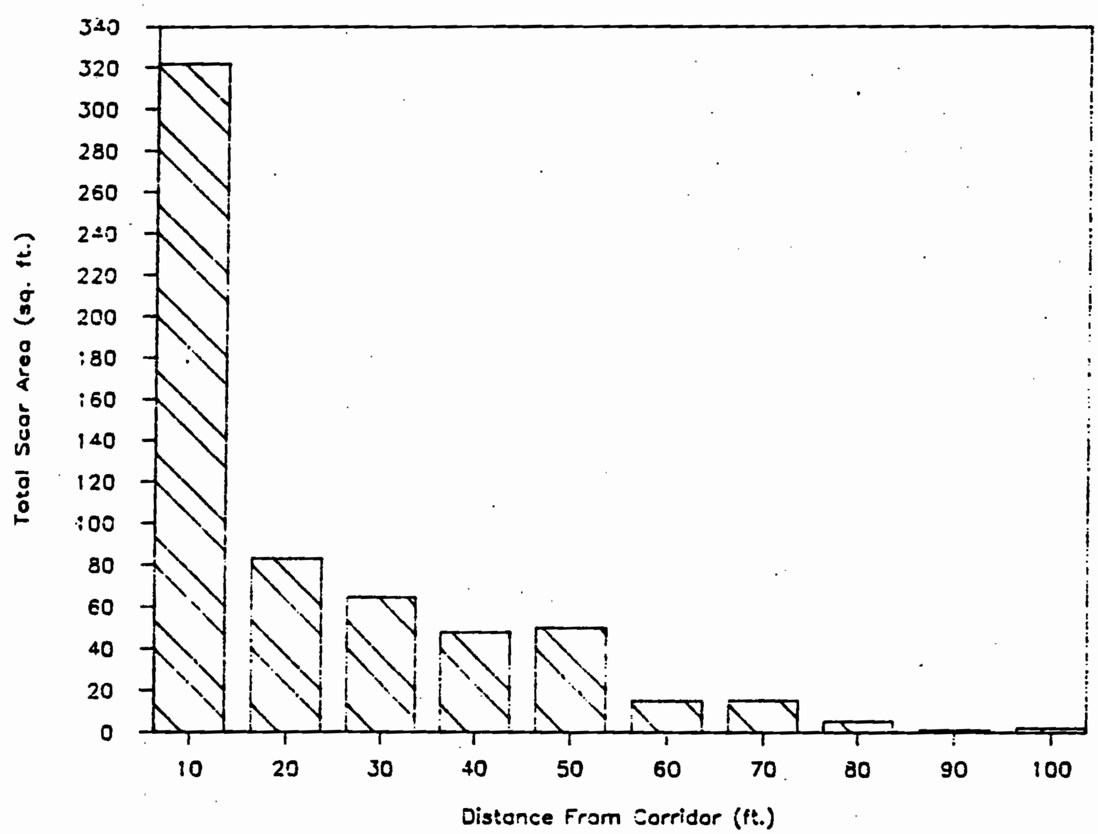


Figure 20. Scar area versus lateral distance from corridor centerline.

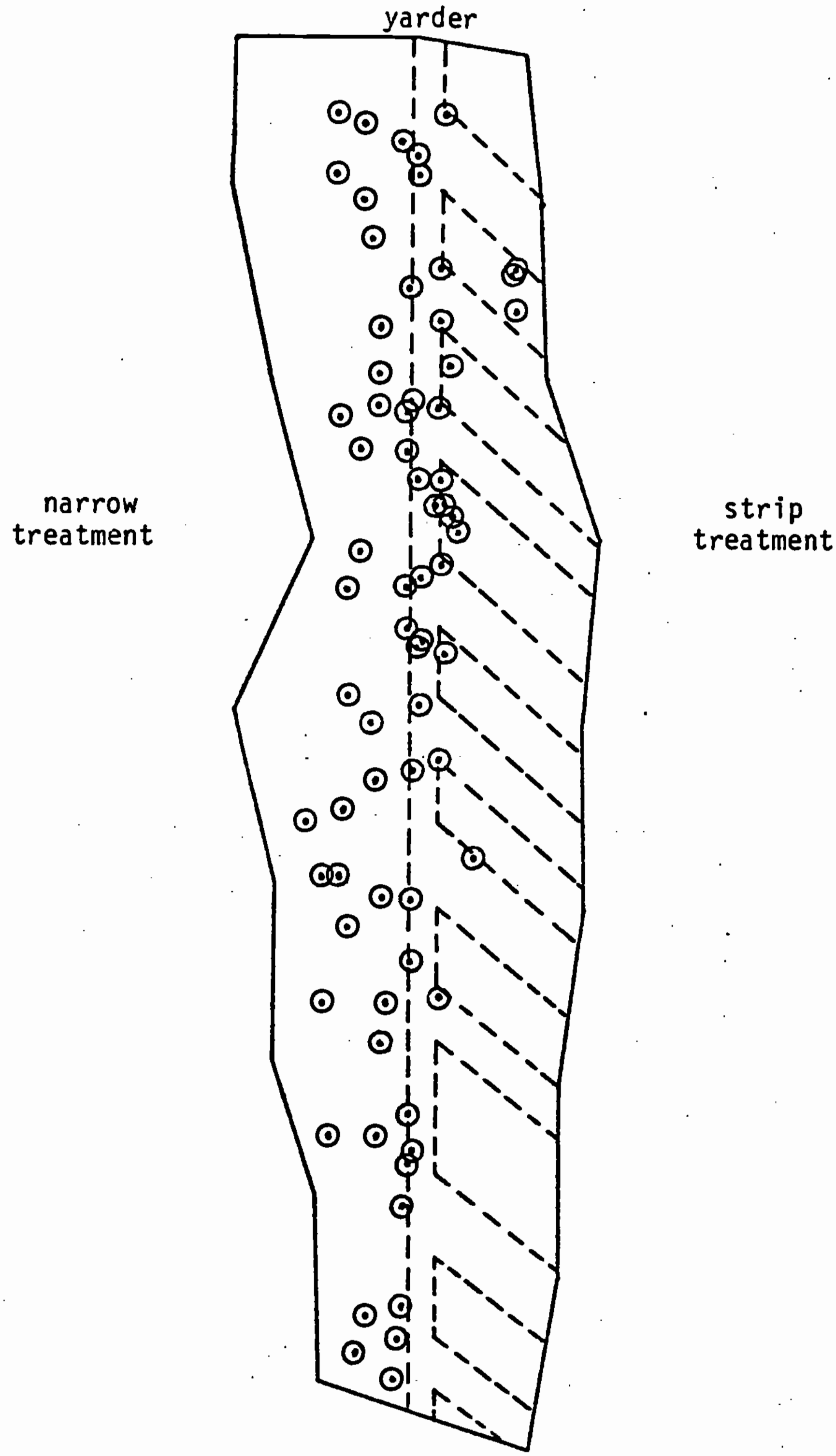
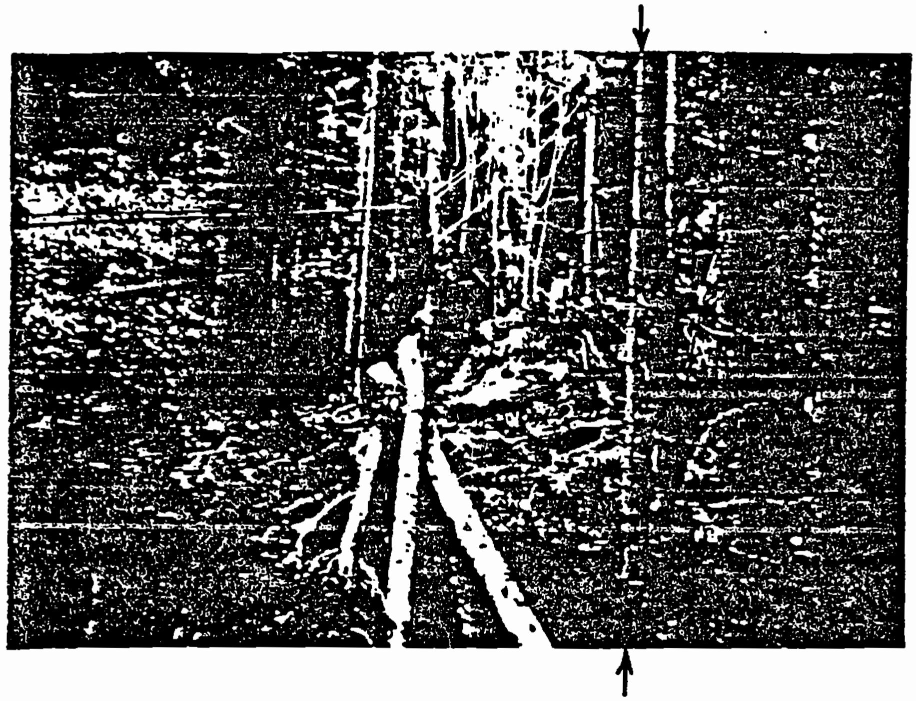


Figure 21. Location of damaged trees in unit 16-1.



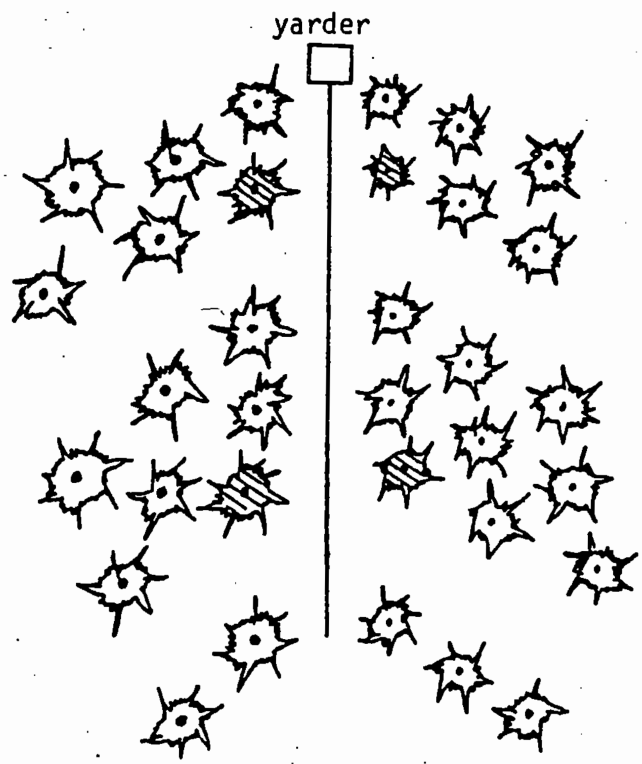


Figure 22. (top) Turn pulled from cut strip. Note rub tree (arrows).

Figure 23. (bottom) Rub trees (cross-hatched) in a strip unit.

However, the yarding lead angle depends largely on the lead of the felled timber. Timber felled out of lead with the corridor will increase the potential for damaging the residual stand. The location of each damaged tree for all detailed damage units are plotted in Appendix C.

Regression Analysis

Regression analysis yielded the model shown in Table 16.

Table 16. Stand damage regression model.

Scar area/turn = (ft^2)	- 0.67103	
	+ 0.39608	(carriage repositions)****
	+ 0.00304	(log angle, degrees)***
	+ 0.01492	(carriage clearance, ft)****
	+ 0.54229	(narrow treatment)****
	+ 0.38205	(rigging slinger)****
	+ 0.54818	(cutter 3)****
	+ 0.41916	(cutter 5)****
r^2 = .21		
n = 531		

**** = significant at the 0.01 probability level
*** = significant at the 0.05 probability level

This model is based on data collected for all yarding turns in the detailed damage units. The estimated mean value of scar area per turn is 0.56 square feet. The standard error of the estimated mean value of scar area per turn is 0.057 square feet. This is how much the estimated mean deviates from the population mean if repeated samples from the population were drawn and the mean of each sample computed. The estimated 95 percent confidence interval is 0.45 to 0.67 square feet meaning the true mean value of scar area per turn would be included in the interval 95 percent of the time.

To determine how the independent variables in the regression equation influence scar area per turn, each variable was increased one standard deviation above its mean value while holding other variables constant. Table 17 shows how each independent variable influences (increases or decreases) scar area per turn.

Table 17. Influence of significant variables on scar area per turn.

variable	mean value plus one standard deviation	increase (+)/decrease (-) above/below mean value of scar area per turn (ft^2/turn)	(%)
carriage repositions	0.51 + 1.00 = 1.51	+0.40	+26.7
log angle	67.83 + 43.62 = 111.45	+0.13	+ 8.9
carriage clearance	18.5 + 10.43 = 28.93	+0.16	+10.5
treatment	indicator variable = 0	-0.54	-36.5
rigging slinger	indicator variable = 0	-0.38	-25.7
cutter	indicator variable = 0	-0.55	-36.9

Thinning treatment has a large influence on the dependent variable. Thinning a stand using a herringbone pattern may reduce scar area per turn 36.5 percent (assuming all other variables are held constant). The human elements of this study (rigging slinger and cutter) have a large influence on scar area per turn. Using experienced personnel may reduce damage by 25.7 percent (rigging slinger) and 36.9

percent (cutter). Carriage repositions also has a large influence and is indirectly related to the rigging slinger since he controls the carriage during the thinning operation. If the rigging slinger is not experienced, scar area per turn may increase 26.7 percent.

The rigging slinger variable is an indicator variable with 1 = less experienced rigging slinger and 0 = most experienced. The least experienced rigging slinger usually worked as a chaser or chokersetter. He had little experience performing the duties of a rigging slinger (selecting the turn of logs and positioning the carriage; two critical elements in yarding through a residual stand). The cutter variable is another indicator variable with 1 = cutters with little thinning experience and 0 = experienced cutters. Five cutters were used in the felling operation. Each cutter was interviewed to determine prior thinning experience and also subjectively ranked according to their abilities shown during the study. Cutter 1 was ranked the best followed by cutters 2-5. The less experienced cutters had limited commercial thinning training. Consequently, the lead of the timber was less optimal than the lead of timber felled by the experienced cutter. The coefficients for cutter 3 and cutter 5 are similar indicating little difference in scar area per turn between the two.

Relative frequencies for the indicator variables are shown in Table 18.

Table 18. Regression model indicator variables.

Indicator Variable	Relative Frequency
rigging slinger	
0 variable	.45
1 variable	.55
	1.00
cutter	
cutter 1 = 1; otherwise = 0	.20
cutter 2 = 1; otherwise = 0	.15
cutter 3 = 1; otherwise = 0	.22
cutter 4 = 1; otherwise = 0	.27
cutter 5 = 1; otherwise = 0	.16
	1.00
treatment	
narrow = 1; otherwise = 0	.29
wide = 1; otherwise = 0	.36
strip = 1; otherwise = 0	.35
	1.00

Thinning treatment was a significant variable. Scar area per turn for the narrow treatment was significantly different from the strip treatment at the 99 percent confidence level. The wide treatment did not enter into the model because it was highly correlated with rigging slinger. Rigging slinger was used in the model because it was correlated with other variables not used in the regression analysis.

Carriage repositioning was also a significant variable; however, a few comments are necessary regarding its coefficient. Normally, the carriage is repositioned during lateral inhaul to avoid damaging the stand; therefore, the coefficient would be negative implying scar area per turn is reduced. In this study, the carriage was usually repositioned after a turn had caused damage; thus, the coefficient is positive. Improper repositioning may be attributed to inexperience of the rigging slinger and fast lateral inhaul speeds resulting in less time for the yarder operator to react to a stop whistle from the rigging slinger.

Two other significant variables were log angle and carriage clearance. A larger log angle results in more scar area per turn. This was observed during the data collection process when a log with a large log angle had to swing into lead with the rest of the turn, increasing its chances to come into contact with a residual tree. The more clearance between the carriage and the ground, the less controlled the turn was during lateral inhaul. The resulting swinging action of the turn increased the chances of damaging the stand.

Descriptive statistics for yarding variables in the regression model are summarized in Table 19.

Table 19. Summary of independent variables in regression model.

Independent Variable and Statistic	All Treatments	Narrow	Treatment Wide	Strip
carriage repositions				
max	5	5	5	4
mean	0.51	0.55	0.58	0.40
min	0	0	0	0
stand dev.	1.00	1.07	1.05	0.84
number of turns	581	167	208	200
log angle				
max	180	178	170	180
mean	67.83	72.21	72.03	59.73
min	0	0	0	0
stand dev.	43.62	40.82	43.04	45.49
number of turns	550	155	205	190
carriage clearance				
max	55	35	35	55
mean	18.50	19.99	16.88	18.97
min	0	0	3	1
stand dev.	10.43	8.68	8.57	12.97
number of turns	562	152	207	197

Lead angle was an independent variable believed to have a significant effect on scar area per turn based on observations made in the field. However, the data collected did not support this observation since lead angle did not enter the model.

Descriptive statistics for independent variables which did not enter the regression model are summarized in Table 20.

Table 20. Descriptive statistics of independent variables not found in the regression model.

Variable	Statistic	All Treatments	Treatment Narrow	Treatment Wide	Treatment Strip
reset turn	max	4	3	3	4
	mean	0.25	0.30	0.24	0.23
	min	0	0	0	0
	stand dev.	0.61	0.68	0.57	0.59
	number of turns	582	168	208	200
slope distance to critical log	max	730	694	436	730
	mean	260.7	260.8	198.1	329.1
	min	0	0	15	5
	stand dev.	173.5	179.2	106.7	199.6
	number of turns	556	157	206	192
lateral distance to critical log	max	140	90	140	120
	mean	40.4	37.4	42.8	40.6
	min	0	0	0	0
	stand dev.	26.1	19.4	28.6	28.3
	number of turns	578	166	206	200
lead angle	max	155	155	141	116
	mean	54.4	66.1	54.8	44.5
	min	0	0	0	0
	stand dev.	31.5	33.3	27.3	31.1
	number of turns	551	155	205	191
percent slope downhill at critical log	max	85	60	60	85
	mean	28.6	29.3	25.8	31.2
	min	0	0	10	0
	stand dev.	14.0	13.2	11.1	16.6
	number of turns	573	163	206	199
number of logs per turn	max	9	9	6	8
	mean	4.0	4.0	4.0	4.1
	min	1	1	1	1
	stand dev.	1.1	1.3	1.0	1.1
	number of turns	582	168	208	200
volume per turn	max	171.7	148.1	137.3	171.7
	mean	62.8	47.5	66.2	71.8
	min	0	0	0	0
	stand dev.	33.5	30.6	28.9	36.2
	number of turns	583	168	209	200

Analysis of Variance Between Thinning Treatments

To determine if there is a significant difference between thinning treatments, an analysis of variance (ANOVA) was constructed based on total scar area per acre for the detailed study corridors only. Data used to construct the ANOVA table is summarized in Table 21. The ANOVA table is shown in Table 22. The hypotheses tested were as follows:

H_o: $\mu_i - \mu_k = 0$, there is no difference between treatment means

H_a: $\mu_i - \mu_k \neq 0$, there is a difference between treatment means

If $F^* < F(1 - \alpha, n-1, n-p)$, then H_o is true, otherwise H_a is true.

Table 21. Number of units (n) and average scar area per acre (x).

	Narrow	Wide	Strip
n	3	3	4
$\bar{x}$	84.78	91.64	17.57

Table 22. ANOVA table.

Source	df	Sum of Squares	Mean Square	F
Between treatments	2	11532.39	5766.20	7.97
Within treatments	7	5062.84	723.26	

$F^*_{(.05,2,7)}$ = 4.74; Since 7.97 > 4.74, one may conclude that average scar area per acre differs from treatment to treatment.

To test whether there is a difference between scar area per acre for any two treatments means, the following t-statistic is used:

$$\text{Standard Error (SE)}_{(x_i - x_k)} = [\text{MSE}(1/n_i + 1/n_k)]^2$$

$$t = \frac{(x_i - x_k)}{SE}$$

If $t^* \leq t\ (1 - \alpha/2,\ n-p)$, then H_0 is true, otherwise H_a is true. Table 23 summarizes the standard error and t-statistics for all combinations of treatments.

Table 23. Standard error and t-statistics for all combinations of treatments.

	Narrow/Wide	Narrow/Strip	Wide/Strip
SE	21.96	20.54	20.54
t	0.245	3.500	3.238
t^*	2.365	2.365	2.365

$t^*_{(.025,7)}$ = 2.365; since 3.500 and 3.238 are both > 2.365, one may conclude that mean scar area per acre for the narrow and wide treatments are significantly different from the mean scar area per acre of the strip treatment. This conclusion differs from the conclusion drawn from the regression analysis because the units of measure are different. Scar area per turn was used in the regression analysis and scar area per acre for analysis of variance.

DISCUSSION

Even though regression analysis was used only as a tool to help identify the influencing harvesting variables, a discussion is necessary regarding the low coefficient of determination.

One problem in this study was data missed during the data collection process. Three types of data was needed for each yarding turn: times for each element in the yarding cycle (detailed time study), yarding and stand variables, and stand damage variables (if damage occurred during a turn). A total of 22 variables were recorded for each turn. Because of human error, haste, or safety, not all of the variables were recorded for every turn. This reduced the sample size approximately ten percent.

Another problem was that not all of the scar area in a unit could be attributed to a turn. This occurred on trees bordering the corridor. It was not always possible to measure scar area along the corridor because of safety reasons and because a corridor tree in the upper part of the span could be scarred by a turn originating from the lower part of the span. Consequently, when safety permitted, a corridor scar was measured and painted when it occurred. After a unit was yarded, the corridor was surveyed and unpainted scars were measured; however, these scars could not be attributed to a specific yarding turn. This resulted in as much as 50 percent of the scar area not available for the regression analysis (Table 24).

The weather had an effect on this study, both directly and indirectly. The study site experienced some of the highest levels of rainfall in the past 30 years during the months of May (fourth highest), June (third highest), and July (highest - when yarding occurred) (Figure 24). Note the different vertical scale for August. Hemlock is easily damaged during the spring when the sap is running and the bark is loose (Wiley, 1975 and Dick, 1976). Bark is easily removed because newly formed cells between the cambium and inner bark have cell walls that have not had time to fully develop. Sap run begins in late March and may continue until late July.

Data was collected in areas of heavy slash and downtimber on soft soil. The first four detailed units (13-1, 16-1, 16-2, 3-1) were yarded during periods of heavy rain and showers. The remaining units (4-2, 6-2, 7-1, 8-1, 9-2) were yarded during warm, sunny conditions. The yarding crew worked 10-hour days with no designated lunch time.

The uncontrollable factors discussed above may help explain the high variability in the data and the resulting low coefficient of determination.

Table 24. Total scar area per turn and per acre for detailed units.

(1) Treatment and Unit	(2) Area (ac)	(3) Total Number of Turns	(4) Number of Turns Causing Damage	(5) Total Scar Area (ft^2)	(6) Scar Area Associated with Turns	(7) Scar Area not Associated with turns (5) - (6)	(8) Scar Area per Turn (ft^2/turn) (6) / (3)	(9) Scar Area per Acre (ft^2/acre) (5) / (2)
narrow								
13-1	0.72	59	30	81.61	43.70	37.91	0.74	113.35
16-1	1.33	86	40	105.93	62.14	43.79	0.72	79.65
7-1	0.90	35	25	62.55	51.02	11.53	1.46	69.50
total	2.95	180	95	250.09	156.86	93.23	0.87	84.78
wide								
3-1	0.64	55	28	53.95	31.58	22.37	0.57	84.30
6-2	0.62	60	29	24.61	20.80	3.81	0.35	39.69
8-1	1.20	94	48	146.87	73.24	73.63	0.78	122.39
total	2.46	209	104	225.43	125.62	99.81	0.60	91.64
strip								
16-1	1.10	41	7	16.31	9.96	6.35	0.24	14.83
16-2	2.49	77	18	32.38	10.48	21.90	0.14	13.00
4-2	1.29	53	14	44.08	17.46	26.62	0.33	34.17
9-2	0.41	24	2	0.20	0.20	0.00	0.01	0.49
total	5.29	195	41	92.97	38.10	54.87	0.19	17.57

* 48.52 ft^2 of scar area could not be associated with narrow or strip treatments in unit 16-1.

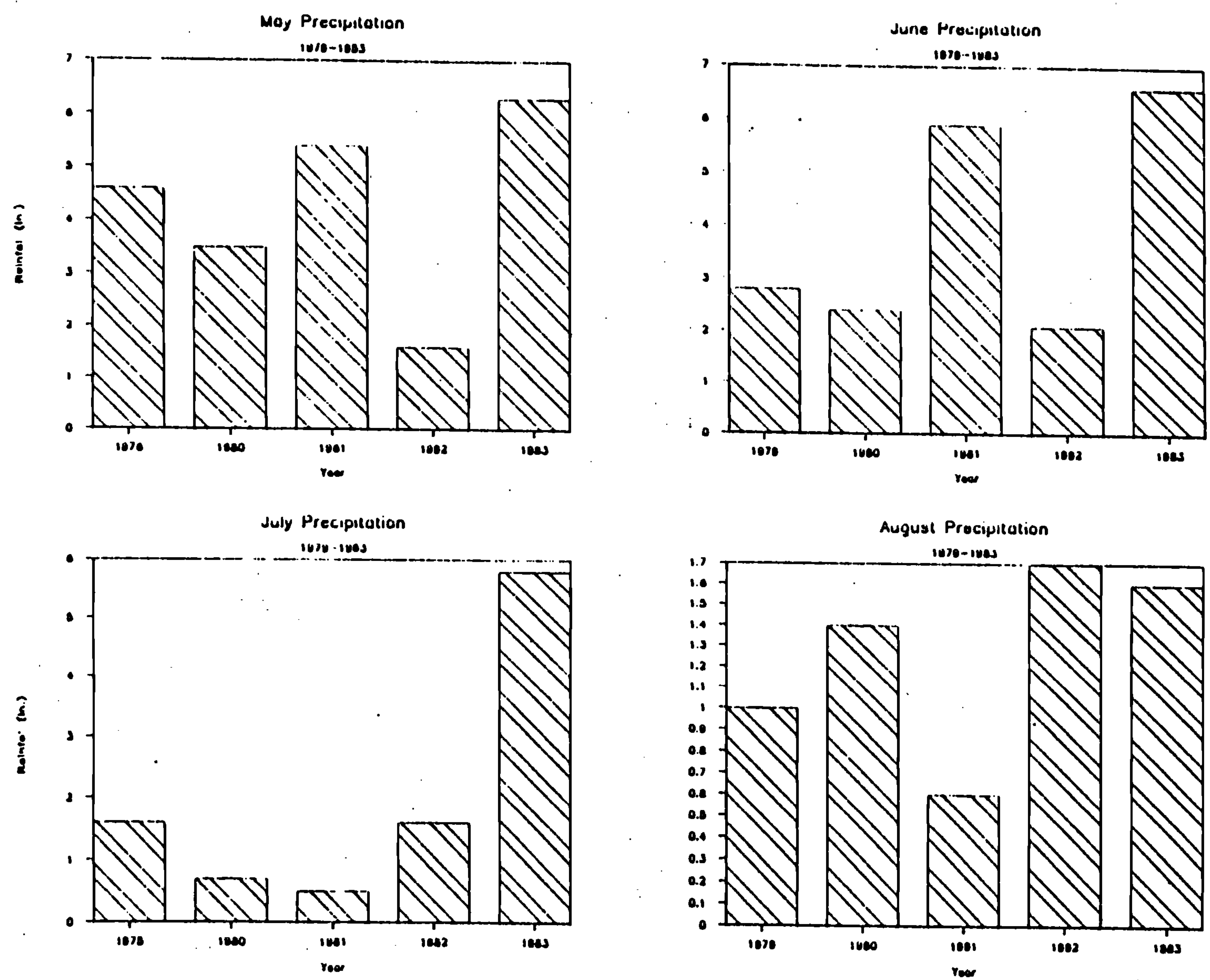


Figure 24. Precipitation for the months of May, June, July, and August; years 1979 to 1983.

Future Volume Losses

Residual stand damage was extensive in both study areas. Of interest to the logging manager is whether the damage sustained in the areas will lead to significant losses in merchantable volume at the time of final harvest. Goheen (1980) found very small volume loss due to decay. Although 41.9 percent of the trees were infected by root and butt decay fungi, a mean of only 2.2 percent of the merchantable cubic foot volume was lost to decay over a 10-year period. To determine if damage sustained in this study may lead to significant volume loss in the future, two regression equations were used; one from Wright and Isaac (1956) and one from Goheen (1980). The equation from Wright and Isaac determines the amount of decay volume based on the age and area of the logging wound. The equation from Goheen determines the cubic foot volume of a hemlock tree based on DBH. Assumptions and calculations, based only on the hemlock species in the narrow treatment, are found in appendix D. From the regression equations, the stand will contain 10,078 cubic feet per acre of hemlock in 15 years. Volume lost to decay will total 202 cubic feet per acre. This means that only 2.0 percent of the merchantable cubic foot volume will be lost to decay. Figure 25 shows the amount of volume lost to decay for this stand if it was harvested at age 45, 60, 75, and 90 years for various percent levels of decayed scars. Even if a high percentage of scars become decayed, the resulting volume loss is small.

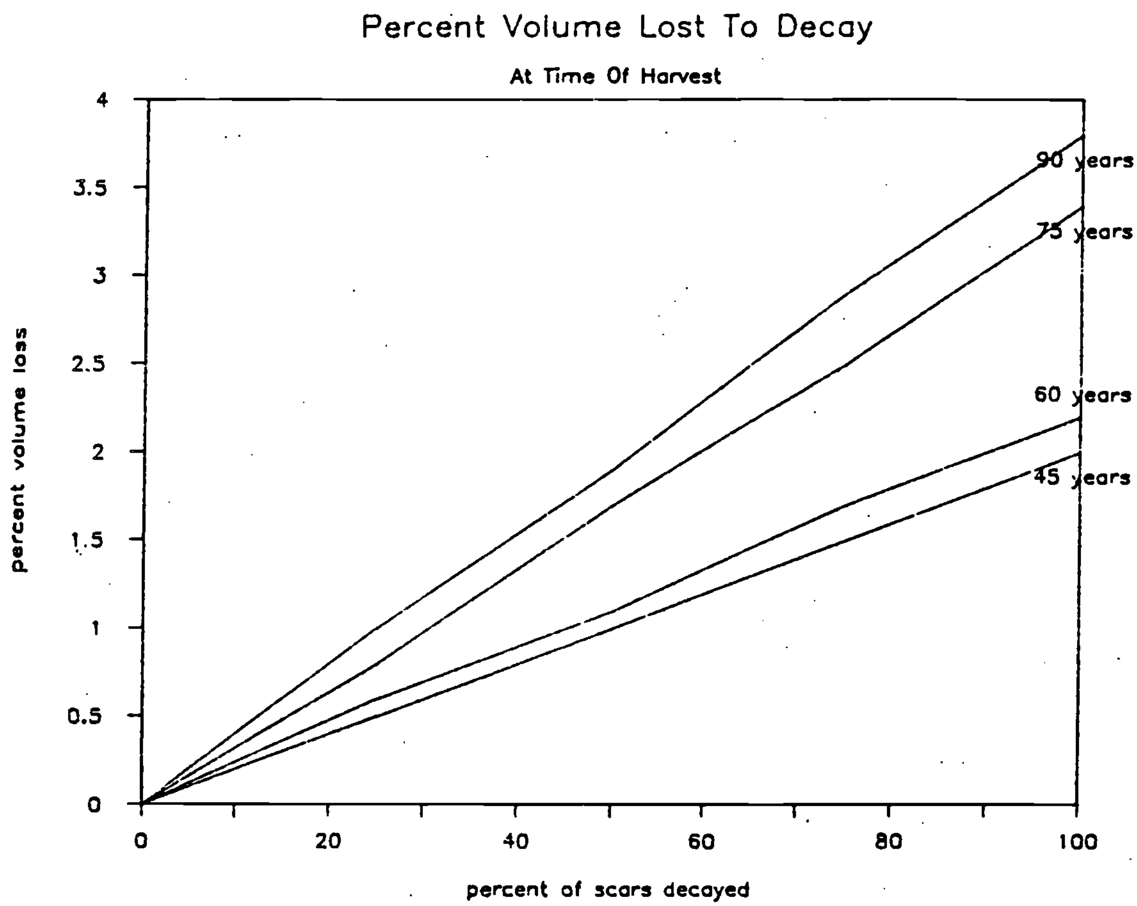


Figure 25. Percent volume loss versus percent scars decayed for stand harvested at ages 45, 60, 75, and 90 years.

SUMMARY

Commercial thinning a young western hemlock-Sitka spruce stand resulted in extensive residual stand damage levels in conventional thinning treatments (84.78 ft^2/acre in the narrow treatment and 91.64 ft^2/acre in the wide treatment) but a significantly reduced level in the herringbone (strip) treatment (17.57 ft^2/acre). Only 12 percent of the residual stand (trees/acre) in the strip treatment was damaged. The narrow and wide treatments experienced much higher levels; 47 and 61 percent, respectively. For all treatments, 52.2 percent of the scars were located along the corridor boundary. Of the total scar area, 66.6 percent was found within 20 feet of the skyline corridor centerline.

Regression analysis was used to develop a model using scar area per turn as the dependent variable. The following variables were found to most significantly influence residual stand damage: number of carriage repositions, log angle, carriage clearance, narrow treatment, rigging slinger, and cutter. The low coefficient of determination may be explained by uncontrollable circumstances involving the weather, crew experience, and variability in the data.

An analysis of variance showed mean scar area per acre for the narrow and wide treatments were significantly different from the strip treatment.

Although damage levels are high, future volume losses may not be significant. Calculations based on damage levels reported in this study suggest that little volume will be lost at the time this stand is harvested.

RECOMMENDATIONS

The ultimate success in a thinning operation depends on the logging crew; however, results can be influenced by the silviculturalist, forest engineer, and sale administrator. The following are recommendations pertaining to these individuals and to others who must plan and implement a silvicultural prescription to commercially thin a young western hemlock-Sitka spruce stand.

1. Prescribe a herringbone thinning pattern to minimize residual stand damage. The angle of the cut strips dictate the direction the timber must be felled; therefore, lead is not a problem.
2. Layout smaller corridor widths (10-15 ft.) and leave rub trees to minimize damage along the corridor boundary.
3. Emphasize the importance of rigging the skyline down the center of the skyline corridor. If the skyline is skewed to either side of the corridor, the chances of pulling over corridor boundary trees when yarding are much greater.

4. Emphasize to cutters the importance of felling to lead and leaving rub trees along corridor boundaries. The same pertains to the logging crew in regards to rigging up and positioning the carriage for each turn. An incentive program to keep residual damage below an acceptable level should be investigated.
5. Conduct thinning operations in late summer or during the winter when the cambium has stopped growing.

FUTURE RESEARCH

Further research is necessary into the relationship between the percent of the residual stand damaged and the resulting merchantable volume loss at the time of harvest. If volume loss is significant, then control measures must be introduced now in order to minimize stand damage during yarding. Data is needed to perform a benefit/cost analysis to determine whether future benefits, in the form of increased merchantable volume, outweigh any increased logging costs associated with the implementation of these control measures.

This study was designed and laid out by Forest Engineering research personnel. The thinning operation, however, was administered by the U. S. Forest Service and felling, rigging, and yarding techniques were left completely to the logging contractor. I suggest a similar damage study where research personnel have control over how the thinning is to be conducted. Results from the two studies (significant variables, damage levels, costs) may then be compared to determine if input from research personnel has a positive or adverse effect on production and costs.

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APPENDIX A

CASCADE HEAD RESEARCH PROJECT AREAS

There are three ongoing studies that make up the research project (Figure A-1). One study investigates the effects of commercial thinning on growth and yield of the stand (Greene, 1982). The objectives of this study are:

1. Determine the effects of three different commercial thinning regimes on diameter and height growth.
2. Determine the amount of damage and subsequent decay to leave trees following logging.
3. Determine the relationship between leaf area and volume production by following their development in the four different treatments.

Plots were established during the winter in 1982. Diameter, height, and scar area data was obtained before and after the harvest operation. Plots will be evaluated at five year intervals starting in 1988 to monitor the affects of scar damage and release on stand growth and yield.

The second study is on logging methods and costs (Kellogg, 1984). There are two phases of study; the first will determine logging costs and operational characteristics between treatments using production studies conducted during harvesting. The main objectives of this phase are:

CASCADE HEAD RESEARCH PROJECT AREAS

Growth, Yield and Scar Damage

Dec. 1981-Mar. 1982
- compartments identified, flagged in field
- plot centers established
- plot measurements

Mar. 1983
- plot measurements

Mar. 1984
- scar measurements

Mar. 1986
- publication

Oct. 1988
- plots reread; at 5 year intervals thereafter

Harvesting Production

Mar. 1982-July, 1983
- planning and layout of corridors

July-Sept. 1983
- felling and logging study areas

Sept. 1983-June 1985
- analysis and dissemination of production and cost data

June 1985-Apr. 1986
- comparing alternative harvesting methods
- economic evaluation

June 1986
- system evaluation; growth and yield, harvesting, and damage impacts

Stand Damage

July-Sept. 1983
- **data collection**

Sept. 1983-June 1985
- **analysis and dissemination of damage data**

July-Sept. 1984
July-Sept. 1985
- blowdown and thinning shock evaluation

Jan. 1986
- **thinning shock growth measurements**

Figure A-1. Flowchart of Cascade Head research project areas. This study is highlighted in bold letters.

1. Develop regression models that predict felling and yarding related to critical thinning treatment variables.
2. Compare felling and yarding costs and production rates between three thinning treatments.
3. Evaluate harvesting differences (production, delays, advantages, disadvantages) between thinning treatments.

The second phase will compare three main yarding alternatives based on production rates and costs:

1. Medium-size yarder (Madill 071) full-cycle thinning used in phase one.
2. Small yarder (Koller K300) full-cycle thinning.
3. Prebunching with a small machine and swinging with a medium-size yarder.

Stand damage is the focus of the third study involving three main topics; residual stand damage, wind damage, and thinning shock. The first topic is the focus of this masters paper. The other two topics will be addressed in a study by Kellogg (1984).

Wind damage will be evaluated in a two-year period after thinning. Study objectives are as follows:

1. Summarize tree characteristics of wind throw following thinning (dbh, total height, crown dimensions).

2. Determine if there is a significant difference in residual tree wind throw between three thinning treatments.
3. Summarize local topographic and surrounding vegetation conditions along with storm characteristics to determine wind throw susceptibility for the study area.

The study site will be surveyed for sunscald following thinning for a period of two years. The main objective of the thinning shock study is to determine if the residual trees are experiencing thinning shock characteristics: height or diameter reduction and sunscald indications.

The three main areas of study (growth and yield, harvesting, stand damage) will be summarized and evaluated by Loren Kellogg as the subjects of his Ph.D. thesis to be completed in June, 1986.

APPENDIX B

EQUIPMENT SPECIFICATIONS

Madill 071 Yarder*	
Engine	Detroit Diesel 8-V-71-N
Rated Engine Horsepower	284 at 2100 rpm
Carrier	Crawler Type
Tower	48 ft. 5 in. Tube Type
Weight	73,500 lbs.
Drum Capacity	
skyline	1900 ft., 1 in. wire rope
mainline	2180 ft., 3/4 in " "
haulback	4400 ft., 5/8 in " "
slackpulling line	2450 ft., 7/16 in " "
strawline	3340 ft., 3/8 in " "
guylines (4)	225 ft., 1 in. " "
Line Speed	1510 feet per minute (main drum, mid capacity)
Line Pull	36,206 lbs. (main drum, mid capacity)
Brakes	Witchita
Danebo MSP Carriage	
Weight	600 lbs.
Skidding Line	150 ft. 5/8 in. wire rope

*Specifications based on S. Madill, Inc. manufacturer's equipment brochure; pulls at stall or clutch slip; speeds at no load.

APPENDIX C

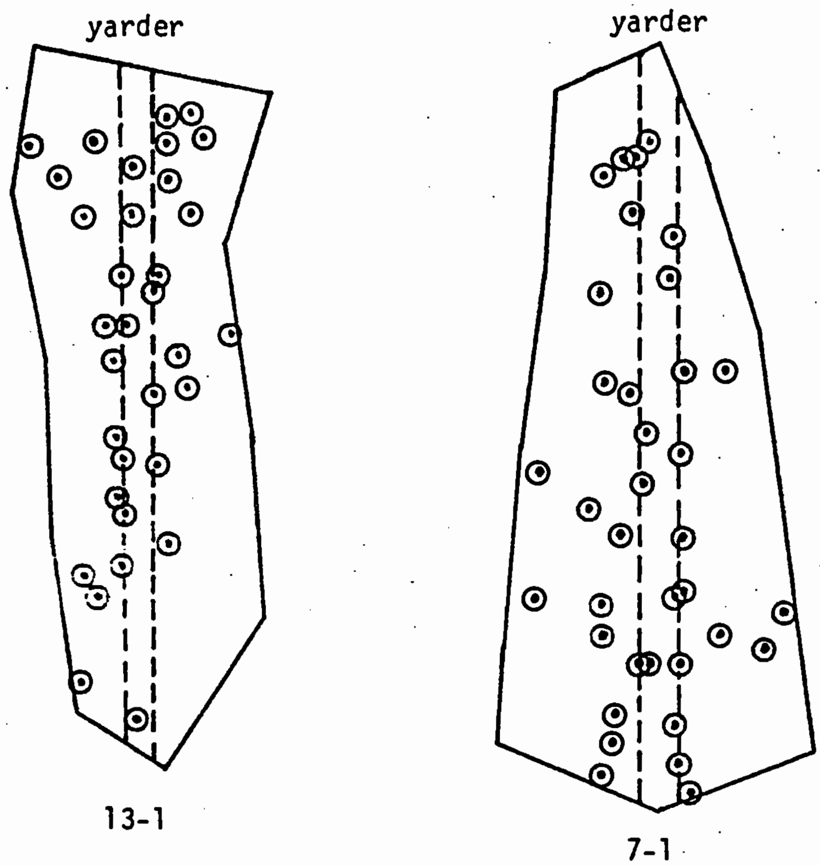

Figure C-1. Narrow treatment units 13-1 and 7-1.

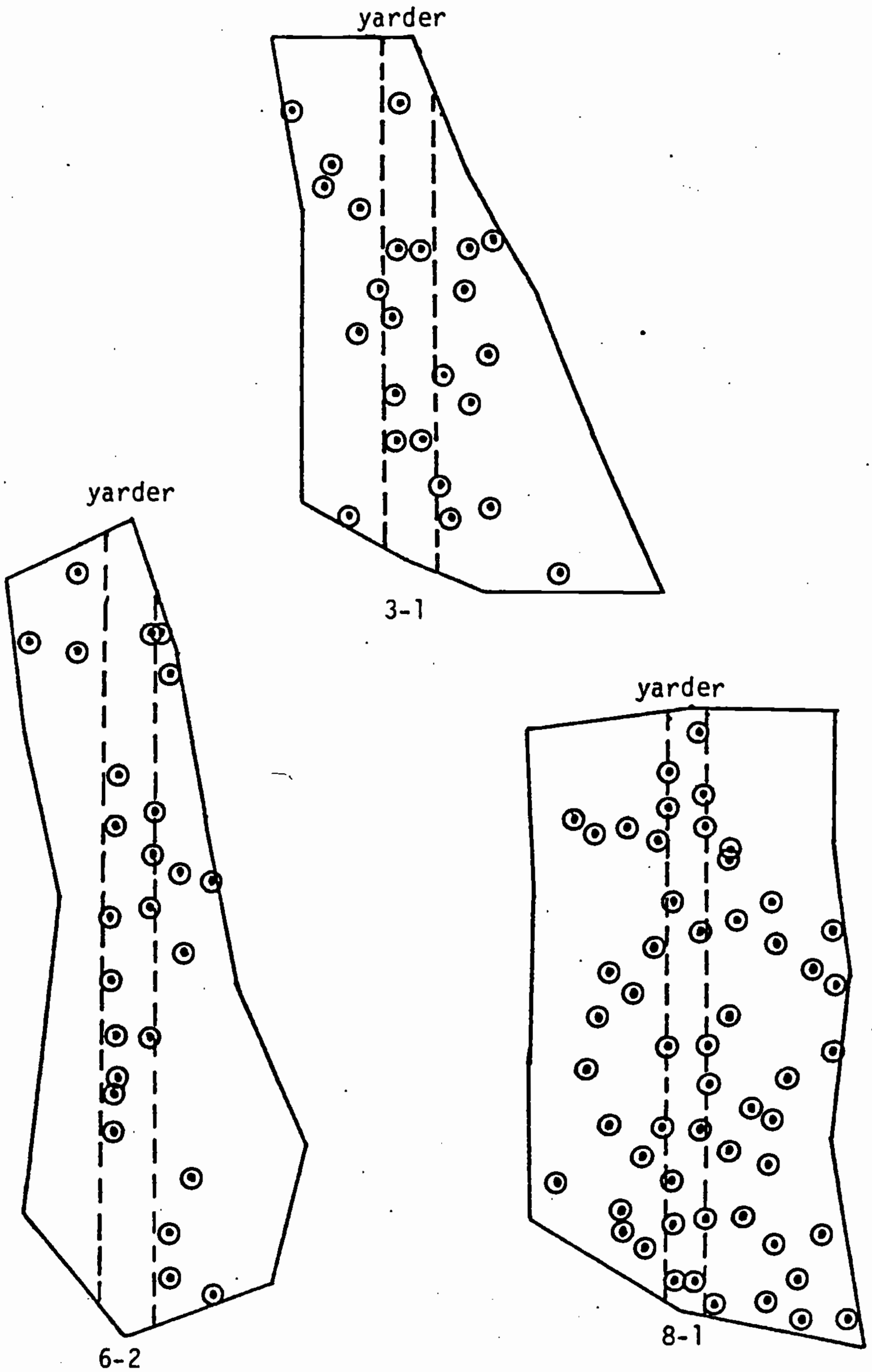

Figure C-2. Wide treatment units 3-1, 6-2, and 8-1.

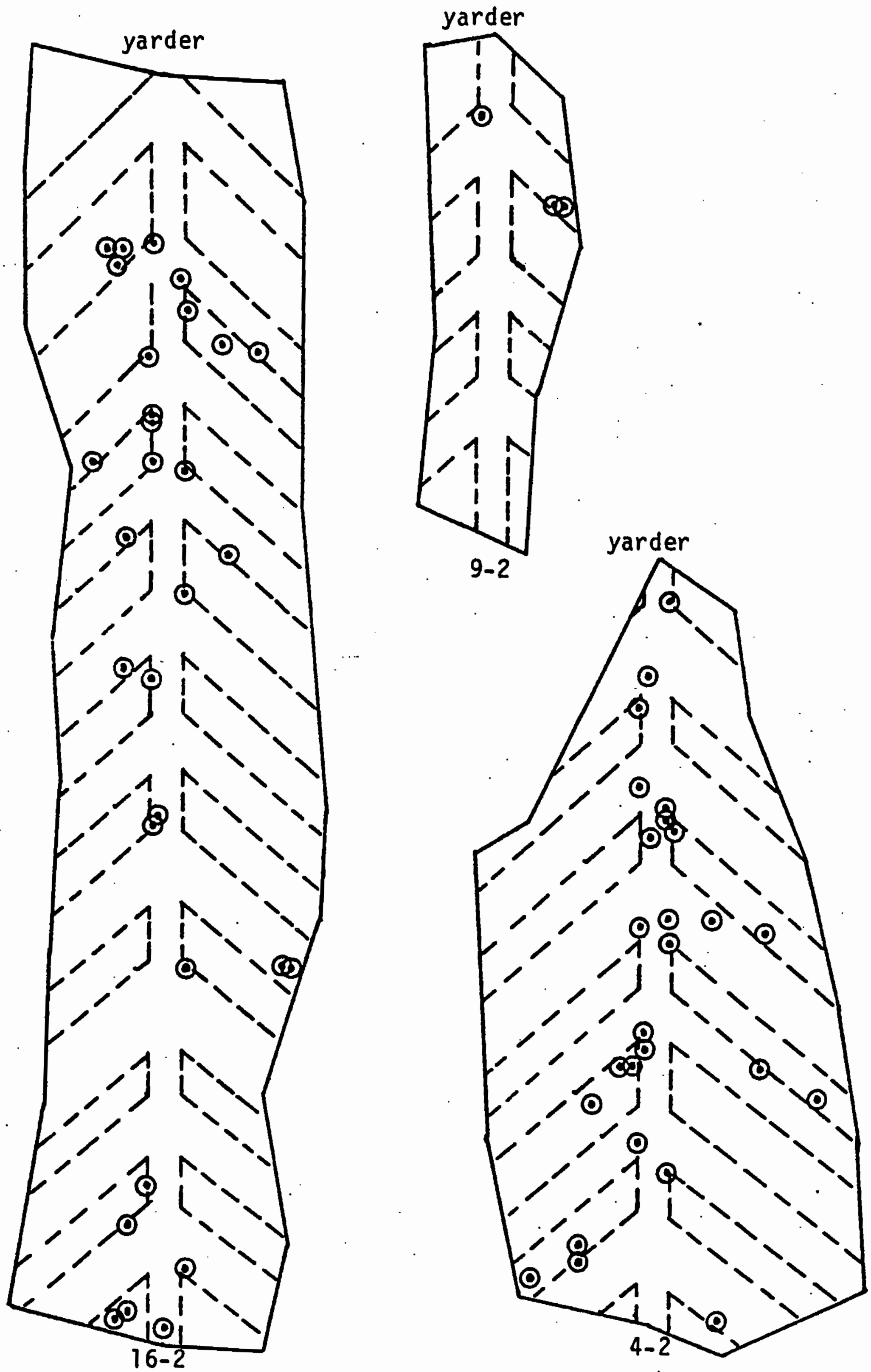

Figure C-3. Strip treatment units 16-2, 9-2, and 4-2.

APPENDIX D

ESTIMATE FUTURE VOLUME LOSS

Volume of hemlock can be determined from an equation.

From Goheen (1980),

$$\text{Hemlock volume, } ft^3 = -0.5673 - 0.7133\,(DBH) + 0.31867\,(DBH^2)$$

$R^2 = .878$

Volume of decay can be determined from an equation.

From Wright and Isaac (1956),

$$\text{Decay volume, } ft^3 = -0.0929 + 0.0944\,X1 + 0.4910\,X2$$

where X1 = wound age in years
X2 = wound area in ft^2

Given: narrow treatment
hemlock species
average DBH (1983) = 15.25 in.
diameter growth rate (1983) = 0.32 in./yr.
trees per acre = 89
scar area per acre = 84.78 ft^2
average scar area = 0.70 ft^2
total number of scars = 358
narrow treatment area = 2.95 acres

Assumptions: clearcut in 15 years (stand age is then 45)
100 percent of the scars become decayed
DBH in 15 years = 15.25 + (15 * 0.32) = 20.05

$$\text{In 15 years, volume } (ft^3) = -0.5673 - 0.7133\,(20.05\text{ in.}) + 0.31867\,(20.05\text{ in.})^2$$

$$\text{volume} = 113.24\ ft^3/\text{tree}$$

$$\text{volume/acre} = (113.24\ ft^3/\text{tree}) * (89\ \text{trees/acre})$$

$$= 10078.11\ ft^3/\text{acre}$$

$$\text{In 15 years, decay volume } (ft^3) = -0.0929 + 0.0944\,(15\text{ yrs.}) + 0.4910\,(.70\ ft^2)$$

decay volume = 1.667 ft^3/scar

total decay volume = (358 scars) * (1.667 ft^3/scar)

= 596.936 ft^3

total decay volume/acre = (596.936 ft^3) / (2.95 acres)

= 202.35 ft^3acre

Volume lost in 15 yrs (%)

= (202.35 ft^3ac) / (10078.11 ft^3/ac)

= 2.01 %