Research Contribution 48

Tractor Thinning Productivity and Costs: Experience from the Willamette Young Stand Project

by

Loren D Kellogg

Chad T Davis

November 2006

Oregon State University

Forest Research Laboratory

The Forest Research Laboratory of Oregon State University was established by the Oregon Legislature to conduct research leading to expanded forest yields, increased use of forest products, and accelerated economic development of the State. Its scientists conduct this research in laboratories and forests administered by the University and cooperating agencies and industries throughout Oregon. Research results are made available to potential users through the University's educational programs and through Laboratory publications such as this, which are directed as appropriate to forest landowners and managers, manufacturers and users of forest products, leaders of government and industry, the scientific community, and the general public.

The Authors

Loren D Kellogg is Lematta Professor of Forest Engineering and Chad T Davis is a research assistant in the Department of Forest Engineering, Oregon State University, Corvallis.

Acknowledgments

The authors wish to acknowledge USDA Forest Service personnel on the Blue River, McKenzie, and Oakridge Ranger Districts of the Willamette National Forest for their cooperation during the project. We also thank the following logging and felling contractors for their cooperation in the detailed and shift-level productivity studies: Card Logging (Springfield OR), Regrowth Enterprises (Springfield OR), Skyline Thinning Company (Springfield OR), and Paul & Arnold Slaven (Oakridge OR). The purchasers of the thinning sales, Rosboro Lumber Company and Swanson-Superior Forest Products Inc., also cooperated. Data were collected with the assistance of temporary and student workers from Oregon State University. Ginger Milota, Chad Bolding, and Francois Oberholzer also assisted with the preparation of this paper.

The research was supported by a USDA Forest Service Willamette National Forest Research Grant, a USDA Wood Utilization Special Grant Project, and Oregon State University's Strachan Forestry Research Fund.

Disclaimer

To Order Copies

Copies of this and other Forest Research Laboratory publications are available from

Forestry Communications Group
Oregon State University
256 Peavy Hall
Corvallis, Oregon 97331-5704
Phone: (541) 737-4271
Fax: (541) 737-4077
Email: forspub@cof.orst.edu
Web site: http://fcg.cof.orst.edu

Please indicate author(s), title, and publication number if known.

Recycled Paper

Editing, word processing, design, and layout by Forestry Communications Group.

Research Contribution 48

November 2006

Tractor Thinning Productivity and Costs: Experience from the Willamette Young Stand Project

by

Loren D Kellogg

Chad T Davis

Forest Research Laboratory

ABSTRACT

Kellogg, LD, and CT Davis. 2006. *Tractor Thinning Productivity and Costs: Experience from the Willamette Young Stand Project*. Research Contribution 48, Forest Research Laboratory, Oregon State University, Corvallis.

Harvesting productivity rates and costs were determined for three silvicultural treatments used in commercial ground-based thinning of young stands to achieve timber management objectives and enhance wildlife habitat. Treatment definitions were based on residual trees per acre (tpa) after thinning. The treatments were light thin (115 residual tpa), light thin with 0.5-ac openings (92 residual tpa), and heavy thin (53 residual tpa). The three study sites were 44- to 46-yr-old stands of Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] located in the Cascade Mountains of west central Oregon. Detailed time studies were conducted on timber fallers and crawler tractors and used to develop multiple linear regression models to predict delay-free felling and skidding cycle times for each site. The independent variables common to the regression models to determine delay-free felling cycle time at all sites were diameter at breast height, number of cuts, and number of limbs cut. Only skidding distance was common to all regression models for determining delay-free skidding cycle time. Total costs for each treatment were obtained by combining felling, skidding, and moving costs for the entire operation. Felling costs ranged from $7.20/CCF to $17.73/CCF. Skidding and loading costs ranged from $15.42/CCF to $38.69/CCF. The cost and productivity results from this study emphasize the importance for forest managers to consider factors such as volume removed and skidding distance when prescribing alternative silvicultural treatments for young Douglas-fir stands.

Contents

List of Tables

List of Figures

Unit Conversions and Abbreviations

1 foot (ft)	= 0.305 meter (m)
1 inch (in.)	= 2.54 centimeters (cm)
1 ft^2	= 0.093 m^2
1 ft^3	= 0.028 m^3
1 ac	= 4,046.87 m^2 or 0.4047 hectares (ha)

CCF	hundred cubic ft (ft^3)
DBH	diameter at breast height
tpa	trees per acre

Introduction

In the Pacific Northwest, federal forest policy and land-use objectives have changed from maximizing timber productivity to ecosystem management. Ecosystem management recognizes that natural systems must be sustained in order to meet future social and economic needs (Kellogg et al. 1999). New information and better understanding of ecological processes highlight the role of biological diversity in sustaining the health and productivity of forest ecosystems (Kaiser 1997).

Many Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] stands are in early seral stages (0–50 yr old) across western Oregon and Washington. Although management objectives for these stands vary, thinning may help achieve differing goals (Hayes et al. 1997). The "Willamette Young Stand Thinning and Diversity Project", a long-term, multidisciplinary research study, was designed to gain understanding of how different management strategies in young stands affect ecosystem diversity.

The primary silvicultural goals of the project were to determine if thinning, underplanting, and creation of snags could accelerate the development of late successional habitat and increase plant and wildlife habitat diversity in 40- to 50-yr-old plantations of Douglas-fir. Logging costs and productivity were subsequently divided on the basis of harvesting system. This paper is part of a series reporting on the harvesting economics. Other major aspects of the overall study included resource management implications, monitoring wildlife and vegetation impacts, tree growth-and-yield responses, mushroom productivity, and social perceptions of the silvicultural methods. A list of published work covering various aspects of the overall project can be found at http://www.fsl.orst.edu/ccem/yst/pubs/pubs.html.

Three harvesting systems used to accomplish the silvicultural objectives were evaluated based on environmental and economical performance: conventional ground-based skidding systems (crawler-tractors), small to mid-sized skyline yarding systems, and cut-to-length systems (harvester/forwarder). The ground-based skidding and skyline yarding systems used chainsaw felling.

The harvesting portion of this study has been published in a series of reports:

- planning and layout costs (Kellogg et al. 1996a)
- logging productivity and costs
    - skyline yarding (Kellogg et al. 1996b)
    - cut-to-length harvesting systems (Kellogg and Spong 2004)
- residual stand damage (Han 1997; Han and Kellogg 1997)
- soil compaction (Allen 1997).

This paper summarizes detailed productivity and cost information for the crawler-tractor logging system.

Small crawler-tractors have proven to be efficient and maneuverable machines for timber transport in thinning studies (Bennett 1993). These systems may also be able to operate effectively in a stand while minimizing residual stand damage and soil compaction (Bennett 1993; Klepac et al. 1999). Using small crawler-tractors and rubber-tired skidders on designated skid trails, with winch lines to reduce soil compaction and residual stand damage, can also be efficient (Garland 1983).

Specific objectives in the harvesting economics studies were to

- create regression equations that predict delay-free cycle times from significant independent variables
- determine productivity rates and costs per hour for felling, yarding, and skidding
- obtain information on delays for use in harvesting simulation
- determine productivity rates and logging costs per unit volume for each component of the logging system (felling and skidding) and for the system as a whole.

This paper addresses these objectives for crawler-tractor harvesting systems and their associations with several silvicultural prescriptions.

Project Description

Study Sites and Treatments

The 208-ac study area was located in the western Cascade Mountains of Oregon, in the Willamette National Forest. The Blue River and McKenzie Ranger Districts were responsible for sale administration during the study. The study was comprised of four timber sales, each applying one or more of four silvicultural treatments. Results from only two of the timber sales were used in this crawler-tractor analysis.

The four silvicultural treatments were designed and labeled as follows:

- Control (C): no thinning (Because there was no harvest in this treatment, it is not discussed further in this paper.)
- Light thin (LT): 110–120 residual trees per acre (tpa)—considered the traditional thinning treatment within sites
- Light thin with openings (LTO): same residual tpa as LT with 0.5-ac openings dispersed systematically throughout the unit, encompassing approximately 20% of the total area
- Heavy thin (HT): 50–55 residual tpa.

For the crawler-tractor portion of the study, the Mill Thin 1 Sale, on the McKenzie Ranger District, had one replication each of the LT and HT silvicultural treatments. The Mill Thin

Table 1. Site characteristics of the light thin (LT), light thin with openings (LTO), and heavy thin (HT) treatment areas before thinning.[a]

Site	Treatment	Study area (ac)	Slope (%)	Stand characteristics Age (yr)	DBH (in.)	Tree height (ft)	Basal area (ft^2/ac)
Mill Thin 1	Both	97	0–35	44	11.9	77	162
	LT	80	0–8	44	11.8	78	175
	HT	17	0–35	44	11.9	75	149
Mill Thin 2	LTO	49	0–20	45	11.8	85	189
Tap Thin	Both	62	0–30	46	10.8	74	144
	LT	33	0–30	46	10.7	78	171
	HT	29	0–27	46	10.9	70	117

[a]The stand characteristics of the study treatments were determined by cruising conifer trees >5 in. DBH.

Table 2. Stand density characteristics before and after thinning and volume harvested for each site/treatment combination.

Site	Treatment	Stand density (tpa) Pre-harvest	Post-harvest	Trees removed (tpa)	Volume harvested[a] MBF/ac	CCF/ac[b]
Mill Thin 1	LT	200	115	85	10.13	31.81
	HT	195	53	142	11.35	35.64
Mill Thin 2	LTO	196	92	104	12.71	39.91
Tap Thin	LT	260	115	145	9.70	30.46
	HT	180	53	127	6.62	20.79

[a]Cruise estimate of Scribner volume harvested does not include volume removed from landings, corridors, and equipment trails.

[b]Derived from conversion factor of 3.14 MBF = 1 CCF, obtained from scale ticket information.

2 Sale, also on the McKenzie Ranger District, had one replication of the LTO silvicultural treatment. The Tap Thin Sale, on the Blue River Ranger District, had one replication each of the LT and HT silvicultural treatments. Specific information for each site and treatment is given in Table 1.

Each site contained second-growth stands of Douglas-fir that had been clearcut during the mid-1940s and early 1950s. After initial logging, the sites were broadcast burned and allowed to regenerate naturally for 2–4 years before being interplanted with Douglas-fir. All stands consisted almost entirely of Douglas-fir with some scattered western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and western red cedar (*Thuja plicata* Donn ex D. Don). The elevation ranged from 2,000 to 2,500 feet. The crawler-tractor harvesting portion occurred in summer at all sites; at Tap Thin, some harvesting was completed in spring for the LT treatment. Table 2 lists detailed stand characteristics for each site and treatment.

The USDA Forest Service planned the sales, implemented treatment boundaries, and marked the leave trees. Thinning was from below, leaving the dominant and codominant trees as residuals. Volume removal for all thinning treatments ranged from 50% to 75% of the pre-harvest stand volume.

Forest Operations

Overview

Each study site was purchased by a private timber company as a lump-sum thinning sale. The term "lump sum" indicates that the purchaser paid for the option to remove all timber not designated a residual tree by the USDA Forest Service. In general, this allowed the purchaser the flexibility of either leaving the fiber material in the woods or utilizing it, depending on the volatile pulp market at the time of harvesting. Certain requirements were designed contractually to ensure that utilization occurred to at least a 4-in. small-end diameter.

The USDA Forest Service planned the preliminary locations of the landings and main skid trails for logging feasibility. Contractors developed their own harvesting plan within the scope of the study. Each timber sale had a different logging contractor and sale administrator. The logging contractors planned and flagged the locations of the designated skid trails. Using skid roads from previous entries was encouraged when layout permitted; due to the randomness of old skid trails, however, this occurred over <15% of the skid trail area (from observation).

After the skid trails were designated, the sale administrator adjusted and approved the skid trails before harvesting. Felling and skidding occurred during the summers of 1995 and 1996. Figure 1 illustrates typical landings and designated skid trails.

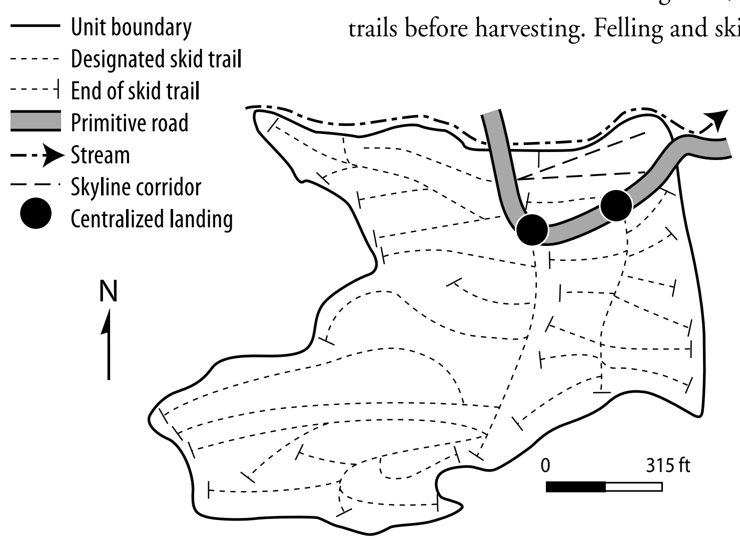

Figure 1. Example of skid trail layout for the Tap Thin Sale (TT) with a light thinning treatment (LT). Skidding was generally downhill to the main skid trails and flat along the main skid trails to the landings.

Felling

Felling at Tap Thin and Mill Thin 2 was subcontracted, whereas felling at Mill Thin 1 was completed by members of the logging crew. In all cases, felling experience for commercial thinning ranged from 3 mo to over 10 yr.

Trees on designated skid roads were harvested before the felling of the unit. Trees were then felled toward the skid roads in a herringbone pattern. Fallers completed the tree limbing and bucking at each site. The minimum requirements for sawlogs were 12 ft long with a 4-in. diameter small end. Fiber material (<4-in. diameter) was not utilized at any site.

Skidding and Loading

Primary log transportation was ground skidding with crawler-tractors. Designated skid trails were spaced approximately 120 ft apart. Most skidding was favorable (loaded downhill) and at <20% slope. Harvesting operations, techniques, and equipment varied slightly among sites, depending on the contractor and unit size. At all sites, skidder operators generally set their own chokers (hot-set), and chasers unhooked the chokers at the landing. Crawlers commonly maneuvered off designated skid trails to position for a favorable winching angle. Tree protection pads were used intermittently alongside main designated skid trails to minimize scarring and damaging residual trees.

Tractor swing roads were used at Tap Thin because of limited road access. Tractor swing roads are additional skidding roads used to connect main skid trails that do not terminate at the roadside landing to the landing. They are used to increase efficiency for long skidding distances by combining smaller turns into larger turns or by utilizing faster forest machinery for transport. At Tap Thin, however, tractor swing roads were used instead of expensive road construction to access the unit. The same turn gathered in the unit was skidded by way of the main skid trail on to the tractor swing road for final deposit at the roadside landing. Swing roads averaged 1,000 ft in length and comprised approximately 10% of the Tap Thin harvest unit.

At Mill Thin 2, log hauling was subcontracted to self-loading trucks, whereas standard loaders and trucks were used at all other sites. The following box summarizes the different skidding equipment and crew type used at each study site.

Mill Thin 1	Mill Thin 2	Tap Thin
Light thin (LT) • 2 CASE 550 crawler-tractors, operated as skidders • D-5 Caterpillar dozer • 5-person crew (3 skidder operators, chaser, loader operator) *Heavy thin (HT)* • 1 CASE 550 crawler-tractor, operated as a skidder • 3-person skidding crew (skidder operator, chaser, loader operator)	*Light thin with openings (LTO)* • 2 CASE 850G crawler tractors, operated as skidders • 3-person crew (2 skidder operators and 1 chaser)	*Light thin (LT)* • John Deere 550 crawler-tractor, operated as a skidder • 3-person crew (1 skidder operator, 1 chaser, 1 loader operator) *Heavy thin (HT)* * 2 John Deere 550 crawler-tractors operated as skidders * 4-person crew (2 skidder operators, chaser, loader operator)

Study Methods

Productivity and costs were evaluated by collecting detailed time-study and shift-level data. Two researchers collected the data for detailed time studies, and the members of the logging crew collected shift-level data.

Detailed Time Studies

Detailed time studies were conducted to collect data on felling and skidding activity cycles, small delays, and productivity rates. Recorded data included productive cycle time elements and other independent variables associated with each activity, as defined in the subsequent Glossaries.

Detailed time data were collected in centimin (0.01 min) with a Husky Hunter II (Husky Computers Limited, United Kingdom) hand-held computer and a SIWORK3 software package (Danish Institute of Forest Technology 1988) and downloaded to a personal computer for analysis. Microsoft Excel (Microsoft Co., Inc., Seattle WA) was utilized to complete forward stepwise multiple linear regression to develop regression equations for predicting delay-free felling and skidding cycle times based on significant (P = 0.05) independent variables. A random 10% of the detailed time study data was withheld from regression equations in order to validate the regression models. Detailed time data were not collected for the HT at Tap Thin because of the small unit and observation size.

Individual trees were identified by painted numbers before felling began. Data recorded for each tree included species, diameter at breast height (DBH), total height, and whether the tree was in a skidtrail corridor. Study areas were chosen ahead of time, which allowed terrain and other stand characteristics to be matched uniformly among the treatments.

Shift-level Studies

Data on scheduled hours and productivity were collected in shift-level studies. One person from each felling and skidding crew was assigned responsibility for filling out production forms daily. Loader operators and self-loader contractors recorded scale ticket information and the number of loads per day. Volume information on piece types was obtained through a random sample of sawlog loads. Average CCF per piece was calculated for each treatment and site.

Cost Analysis

Logging costs were calculated for the owning, operating, and labor costs associated with the specific equipment and personnel used at each study site (Appendix). The researchers developed costs for this report using the PACE program (Sessions and Sessions 1986), not attempting to simulate site-specific contract bids. Costs were divided by the productivity rate to determine cost per unit ($/CCF) at each site. Dollars are reported as 1997 dollars; this value coincides with the time of the study and other Willamette Project harvesting publications.

Log volume information was obtained from scale ticket information provided by the purchaser's mill yard. A cubic-foot-volume conversion factor (3.14 MBF = 1 CCF) was obtained (Kellogg et al. 1997) and applied to all sites. Volume information was used to predict productivity per hour from the effective hour and regression models. The delay-free cycle time was determined by inserting average values for the independent variables into the regression equations.

The stump-to-truck logging costs do not include profit and risks allowances. Planning and layout costs, reported by Kellogg et al. (1997), and sale administration expenses also were not included in the cost analysis.

The following components were used to calculate productivity rates and costs for felling and skidding:

- *effective hour (min/hr)*—productive time, determined from the percent of time lost in delays (felling or skidding) for a site. For example, a site with 20% of its time in delays would have an effective hour of 60(1 – 0.20) = 48 min/hr.
- *delay-free cycle time*—determined by inserting the average values for the observed independent variables into the felling or skidding regression equation formulated for a site. Units for felling are min/tree. Units for skidding are min/turn.

- *volume per cycle*—volume per piece type (log and top), determined from the shift-level study, and total pieces per cycle, determined from the detailed time study. Units for felling are CCF/tree. Units for skidding are CCF/turn.
- *owning, operating, and labor costs ($US/hr)*—determined from a cost appraisal of the specific equipment and personnel used at each site (Appendix)
- *net:gross timber scale*—a ratio of net volume (no defects in wood) to gross volume, determined from the shift-level study

The following components were used to calculate productivity rates and costs from data collected during the shift-level study:

- *productivity rate* (CCF/hr) = (effective hr/delay free cycle time)(volume per cycle)
- cost ($/CCF) = (owning, operating, and labor costs)/[(productivity rate)(net:gross timber scale)]

Scope of Report

Because the analysis of harvesting systems was integrated with a larger, multidisciplinary study, this specific study had no influence on overall treatment definitions and design. The combination of initial stocking levels and treatment definitions relating to residual trees per acre determined the stems per acre removed for each treatment (Table 2). Thus, silvicultural treatments did not necessarily correspond to the volume or stems per acre harvested. For example, the HT removed more tpa than the LT at Mill Thin 1, but fewer at Tap Thin. The same relationship existed with volume removed. Additionally, fewer trees were removed per acre in the HT at Mill Thin 1 than in the LT at Tap Thin. For these reasons, along with problems with data collection for felling at Tap Thin, this paper reports harvesting costs of the different silvicultural regimes without drawing firm comparisons or conclusions about cost effects of treatments across sites.

Comparisons of the treatment effects on harvesting costs, while worthwhile, would require a more thorough control of study design than afforded here. First, harvesting units should be more similar in terms of stocking, past management, and harvest unit layout. Second, replications of treatment should strive for similar residual stands, i.e., removal of similar numbers of tpa and volume at each replication. Treatments analyzed for this report were carried out in dissimilar conditions. Therefore, we describe the range of costs for alternative silvicultural treatments for young stand management without making firm comparisons among treatment harvesting costs.

RESULTS

Regression Equations

Glossary 1: Cycle time elements measured for felling

Cycle element	Definition
Travel and preparation	Travel between trees; starts when bucking or limbing is complete, ends when the felling of the next tree starts
Fell	Starts when chainsaw touches the tree, ends when tree hits the ground
Limb and measure	Starts when the tree hits the ground, ends when bucking cut starts
Buck	Starts (usually after "limb and measure") when chainsaw begins cutting a horizontal cross-section of the main stem, ends when "travel" or "limb and measure" begins
Delays	The time involved with individual delays

Table 3. Average felling cycle from the detailed time study for each site.

	Mill Thin 1		Mill Thin 2		Tap Thin	
Cycle component[a]	Average time (min/tree)	% of cycle	Average time (min/tree)	% of cycle	Average time (min/tree)	% of cycle
Travel and preparation	0.63	9.5	0.48	10.4	0.55	11.6
Fell	0.82	12.2	0.60	13.0	0.49	10.3
Limb and measure	2.78	41.5	1.22	26.3	1.85	38.6
Buck	0.34	5.0	0.20	4.3	0.17	3.6
Delay-free cycle[b]	**4.57**	**68.2**	**2.51**	**54.0**	**3.06**	**64.0**
Delays	2.13	31.8	2.14	46.0	1.72	36.0
Total felling cycle	**6.70**	**100.0**	**4.65**	**100.0**	**4.79**	**100.0**

[a]Defined in Glossary 1.

[b]Actual average delay-free cycle.

Felling

All sites

At each site, "limb and measure" constituted the largest percentage of the productive cycle (Table 3). Delays ranged from 31.8% of the total cycle at Mill Thin 1 to 46.0% at Mill Thin 2. The independent variables common to the regression equations for all sites were *DBH*, number of limbs cut (*Limbs*), and number of bucking cuts (*Cuts*) (Tables 4–6).

Mill Thin 1

The average total cycle time for felling was 6.70 min over both treatments (Table 3). "Limb and measure" required 41.5% of the total felling cycle and felling delays, 31.8%. The three most common delays were "mechanical", "personal", and "discussion" (Figure 2).

The regression model developed from the detailed time studies to predict delay-free felling cycle times for the Mill Thin 1 site was

Fell time (min/tree) = -0.787 - 1.167 *Treatment* (0–1) + 0.375 *DBH* (in.) + 0.019 *Limbs* (no.) + 0.199 *Cuts* (no.) + 1.275 *Wedge* (0–1) [1]

(Adjusted R^2 = 82.6%; standard error = 1.030; sample size = 269 trees)

where all variables are as defined in Glossary 2.

Statistics for the significant ($P < 0.05$) independent variables are summarized in Table 4. The significance of *Treatment* indicated that the LT and HT treatments differed significantly in determining delay-free cycle time. Two independent variables, *Cuts* and *Logs*, were strongly correlated ($r = 0.74$). Substituting *Logs* for *Cuts* in the model negatively affected R^2 by only 0.1%. When both variables were included in the model, one was nonsignificant. In the stepwise approach, *Cuts* proved significant first, and we chose to include this variable in order to stay consistent with other sites.

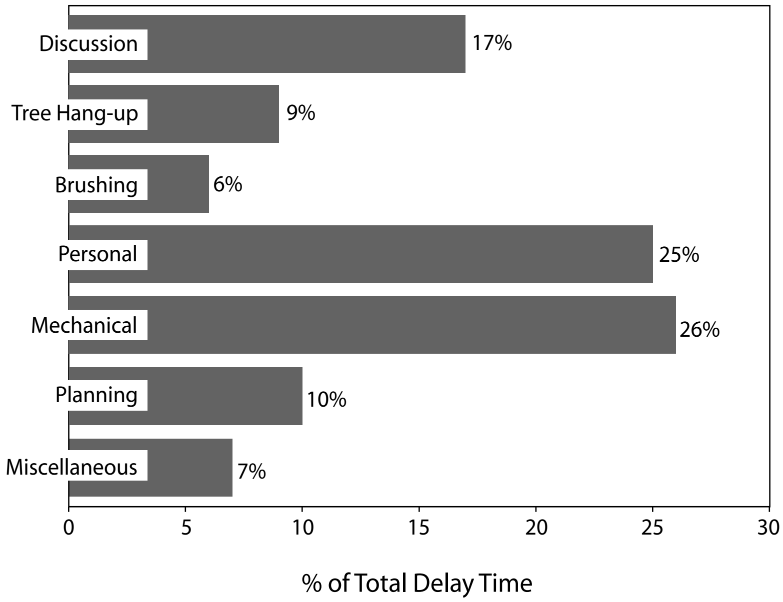

Figure 2. Breakdown of felling delays from the detailed time study at the Mill Thin I site.

Glossary 2: Independent variables measured for felling

Variable	Definition
Cuts	Cross cuts (cut outs, topping, bucking) (no.)
DBH	Diameter at breast height (in.)
Limbs	Tally of each limb cut with the chainsaw (no.)
Logs	Stems that are bucked at both ends (no.)
Tops	Stems that have one buck cut or attached top, no limbing or bucking (no.)
Slope	Average ground slope at felling (%)
Species	Species being felled 0 = Douglas-fir 1 = western hemlock 2 = western red cedar
Treatment	
Mill Thin 1 and	Light Thin (LT) = 0
Tap Thin	Heavy Thin (HT) = 1
Mill Thin 2	Light Thin with openings (LTO) only treatment 0 = not in openings, 1 = in openings
Wedge	0 = no wedges, 1 = wedges used

Table 4. Summary statistics for significant independent variables of the felling regression equation for Mill Thin 1 [Eq. 1] in the light thin (LT), heavy thin (HT), and both treatments.

	Treatment		
	LT	HT	Both
Variable[a]	*n* = 187	*n* = 82	*n* = 269
Treatment[b]			
Average	0.00	1.00	0.30
Standard deviation	0.00	0.00	0.46
Range	0	1	0–1
DBH (in.)			
Average	9.54	10.58	9.86
Standard deviation	3.27	3.74	3.45
Range	5–19.4	5.2–21.2	5–21.2
Limbs (no.)			
Average	76.45	64.35	72.76
Standard deviation	40.75	40.87	41.09
Range	0–173	0–169	0–173
Cuts (no.)[c]			
Average	2.00	2.44	2.12
Standard deviation	0.80	1.49	1.10
Range	0–5	0–9	0–9
Wedge[b]			
Average	0.16	0.26	0.19
Standard deviation	0.37	0.44	0.39
Range	0–1	0–1	0–1

[a]Defined in Glossary 2.
[b]Indicator variable, with a value of 0 or 1.
[c]"Cuts" and "Logs" were strongly correlated (r = 0.74). If substituted for "Cuts" in the model, "Logs" is significant (R^2 = 82.8%).

Mill Thin 2

The average total cycle time was 4.65 min for the only treatment, LTO (Table 3). "Limb and Measure" required 26.3% of the total felling cycle. Felling delays made up 46.0% of the average cycle time; the major delays were "miscellaneous", "mechanical", and "planning" (Figure 3). Two of the four "miscellaneous" delay occurrences, however, were ~20 min each, whereas the average delay occurrence for all categories was 2.14 min.

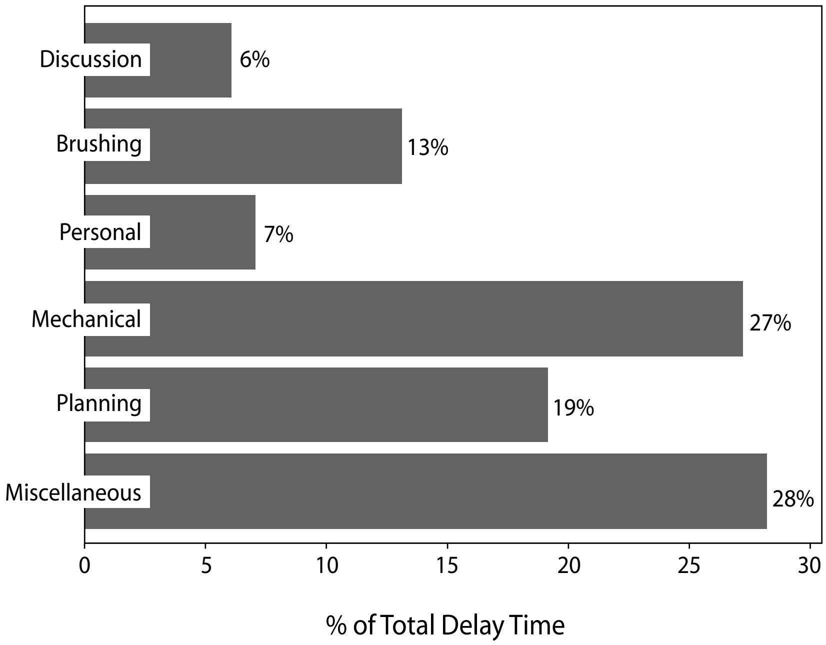

Figure 3. Breakdown of felling delays from the detailed time study at the Mill Thin 2 site.

The regression model developed from the detailed time studies to predict delay-free felling cycle times for Mill Thin 2 was

Fell time (min/tree) = 0.197 + 0.063 *DBH* (in.) + 0.024 *Limbs* (no.) + 0.370 *Cuts* (no.) [2]

(Adjusted R^2 = 69.0%; standard error = 0.590; sample size = 64 trees)

where all variables are as defined in Glossary 2.

Statistics for the significant independent variables (P < 0.05) in the regression equation are summarized in Table 5.

Table 5. Summary statistics for significant independent variables in the felling regression equation for Mill Thin 2 [Eq. 2] in the light thin with openings (LTO) treatment.

Variable[a]	Treatment LTO $n = 64$
DBH (in)	
Average	13.35
Standard deviation	4.11
Range	6.9–24.6
Limbs (no.)	
Average	30.92
Standard deviation	23.67
Range	0–99
Cuts (no.)	
Average	1.95
Standard deviation	0.52
Range	1–3

[a]Defined in Glossary 2.

Tap Thin

Only the LT treatment was analyzed at Tap Thin, as sample size in the HT treatment was too small. The average total felling cycle time was 4.79 min (Table 3). "Limb and measure" required 38.6% of the total felling cycle, and delays, 36%. "Mechanical" and "brushing" were the top two categories of delays (Figure 4).

The regression model developed from the detailed time studies to predict delay-free felling cycle times for the Tap Thin site was

Fell time (min/tree) = 0.208 + 0.140 *DBH* (in.) + 0.040 *Limbs* (no.) - 0.052 *Slope* (%) - 0.576 *Species* (0-2) + 0.546 *Cuts* (no.) [3]

(adjusted R^2 = 79.2%; standard error = 0.734; sample size = 121 trees)

where all variables are as defined in Glossary 2.

Statistics for the significant ($P < 0.05$) independent variables are summarized in Table 6. Again, *Cuts* and *Logs* were strongly correlated ($r = 0.97$). Substituting *Logs* in the model for *Cuts* negatively affected R^2 by only 0.3%. We included *Cuts* here for the same reason as at Mill Thin 1.

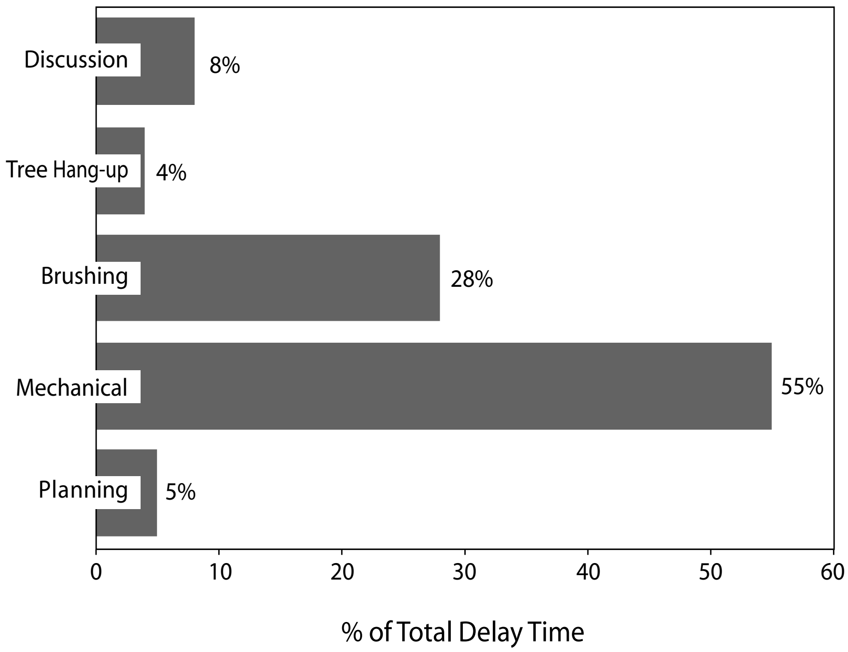

Figure 4. Breakdown of felling delays from the detailed time study at the Tap Thin site.

Table 6. Summary statistics for significant independent variables in the felling regression equation for Tap Thin [Eq. 3] in the light thin (LT) treatment.

Variable[a]	Treatment LT *n* = 121
DBH (in.)	
Average	12.52
Standard deviation	4.17
Range	6–24
Limbs (no.)	
Average	23.66
Standard deviation	17.47
Range	0–76
Cuts[a] (no.)	
Average	1.80
Standard deviation	0.68
Range	1–3
Slope (%)	
Average	15.04
Standard deviation	3.45
Range	10–20
Species (0–2)	
Average	0.09
Standard deviation	0.29
Range	0–1

[a]Defined in Glossary 2.

Skidding

All sites

The breakdown of the total skidding cycle for each site is shown in Table 7. Delays ranged from 15.1% at Mill Thin 1 to 23.0% at Mill Thin 2. The only independent variable common to the regression models for all sites (Tables 8–10) was *Skidding distance*.

Mill Thin 1

The average total cycle time was 8.88 min (Table 7). The three most time-consuming components of the total felling cycle were "winch out", "travel in loaded", and "travel out empty". Delays were 15.1% of the average cycle time; the major delays were "miscellaneous", "mechanical", and "skid trail obstruction" (Figure 5).

The regression model developed from the detailed time studies to predict delay-free skidding cycle time at Mill Thin 1 was

Skid time (min/cycle) = 2.181 + 0.344 *Logs* (no.) + 0.825 *Chaser* (0–1)
+ 0.004 *Skidding distance* (ft) + 0.026 *Line* (ft) + 0.329 *Lang* (0–3) + 1.307 *Road* (0–1) [4]

(adjusted R^2 = 41.7%; standard error = 1.21; sample size = 189 turns)

where all variables are as defined in Glossary 4.

Glossary 3: Cycle time elements and variables measured for skidding

Cycle element	Definition
Travel empty	Begins when the skidder leaves the landing or at end of unhook if no decking, ends when skidder slows down on designated skid trail and begins planning for the next turn or leaves skid trail and positions skidder for winching
Position	
operator sets chokers	Begins when skidder slows or leaves skid trail and positions skidder for winching, ends when operator leaves cab
with choker setters	Begins when skidder stops or leaves skid trail and positions skidder for winching, ends when choker setter grabs winch line
Winch-out	
operator sets chokers	Begins when operator leaves the cab, ends when operator hooks first log in turn
with choker setter	Begins when choker setter grabs winch line, ends when choker setter hooks first log in turn
Hook:	
operator sets chokers	Begins when operator hooks first log in turn, ends when operator moves to next log
with choker setter	Begins when choker setter hooks first log in turn, ends when choker setter moves to next log or back to skidder
Line out & hook	These elements repeat until all logs are hooked. Line out continues after the operator or choker setter leaves the first log and ends when they reach the second log, where hooking begins (and so on). Line out ends when winching begins (inhaul of logs to skidder).
Winch	Begins when winching begins, ends when winch line is locked
Reposition	Occurs between "winch" and "travel loaded", including any movement between two elements and any additional winching of the line in excess of what was initially pulled out to hook logs
Travel loaded	Begins when winch line is locked, ends when the skidder stops on the landing or drops winch line
Unhook	Begins when skidder stops on landing (or drops winch line), ends when skidder moves after the winch line is locked
Deck	Begins when skidder moves after the winch line is locked, ends when skidder leaves the landing

Table 7. Average skidding cycle determined from the detailed time study for each site.

Cycle component[a]	Mill Thin 1		Mill Thin 2		Tap Thin 1	
	Average time (min/tree)	% of cycle	Average time (min/tree)	% of cycle	Average time (min/tree)	% of cycle
Travel out empty	1.62	18.3	1.39	13.7	3.23	23.2
Positioning	0.54	6.0	0.31	3.0	0.39	2.8
Winch-out	1.95	21.9	1.25	12.3	2.03	14.5
Hook	0.41	4.6	1.04	10.2	0.58	4.2
Winch	0.39	4.4	0.36	3.6	0.56	4.0
Travel in loaded	1.87	21.1	1.63	16.1	2.52	18.1
Unhook	0.57	6.4	0.75	7.4	1.11	8.0
Deck	0.19	2.1	1.09	10.7	0.52	3.7
Delay-free cycle[b]	**7.54**	**84.9**	**7.83**	**77.0**	**10.94**	**78.5**
Delays	1.34	15.1	2.34	23.0	2.99	21.5
Total skidding cycle	**8.88**	**100.0**	**10.17**	**100.0**	**13.93**	**100.0**

[a]Defined in Glossary 3

[b]Actual average delay-free cycle.

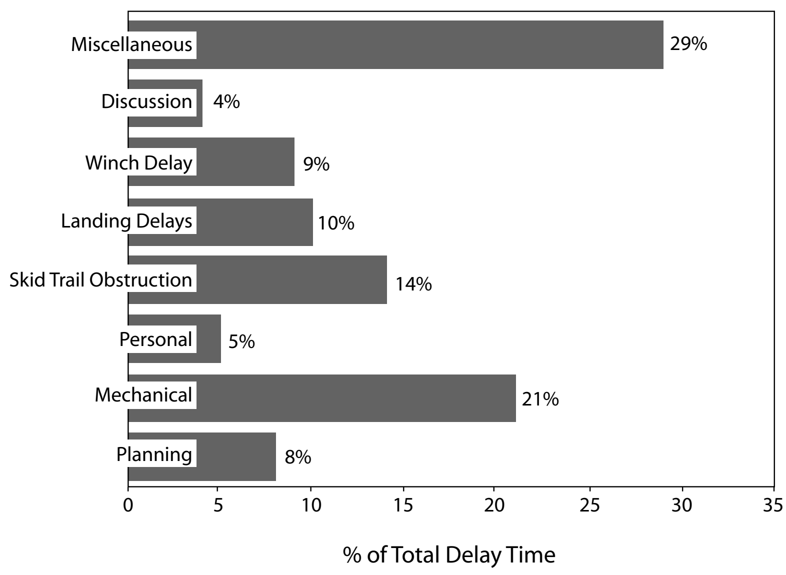

Figure 5. Breakdown of skidding delays from the detailed time study at the Mill Thin 1 site.

Glossary 4: Independent variables measured for skidding

Variable	Definition
Chasers	0 = chaser assisted in the unhooking process, 1 = no chaser assisted the operator
Chokers	Chokers/turn (no.)
Damage	Trees damaged/turn, with damage defined as a tree scar or ding larger than an egg (approximately 1 in. × 2 in.) (no.)
Favor	Average winch line slope between the skidder and load: 0 = adverse slope, 1 = favorable slope
Lang	The angle that the winch line makes with respect to the skidder as it is pulled off (parallel with direction of haul) into the stand. Indicator variables are designated to a range of angles: 0 = 0–30° 1 = 30–60° 2 = 60–90° 3 = >90°
Lead	Lead to winch line is defined as the position of the log with respect to the line in a zone of ±30° off a projection of the winch line.
Line	Winch line distance, the maximum distance between the skidder and the furthest log. An accuracy of ±2 ft is required.
Logs	Logs (any stem bucked both top and bottom) brought to landing for given cycle (turn) (no.)
Off	Distance tractor pulls off designated skid road (no. of ½-vehicle lengths)
Pod	Location of turn regarding opening or thinning, applying only to the light thinning with openings (LTO): 0 =no openings, 1 = openings
Road	Indicates if the turn came from logging the stand or from clearing the roads: 0 = stand, 1 = road
Skidding distance	Distance (ft) that skidder travels from landing to winch position. Preskidding layout of slope distances along designated skid trails was measured and marked on residual trees every 50 ft. The distance can be determined between the measure trees to the location of the skidder (± 5 ft) during the travel time of the skidder.
Slope	Effective skid road slope, the average slope the skidder travels along skid road. Profiles of representative skid roads were generated when skidding distances were measured. The % slope and slope distance were recorded along with the road number. To reduce comparison problems, skid roads were consistent in slope profiles and void of any major slope changes.
Tops	Tops (only one cut or the tops still attached) brought to landing for given cycle (turn) (no.)
Treatment	An indicator variable used to discern treatment assignment for observations: 0 = Light thin (LT), 1= Heavy thin (HT)

Table 8. Summary statistics for significant independent variables in the skidding regression equation for Mill Thin 1 [Eq. 4] in the light thin (LT), heavy thin (HT), and all treatments

	Treatment		
	LT	HT	Both
Variable[a]	$n = 97$	$n = 92$	$n = 189$
Logs (no.)			
Average	4.19	3.82	4.01
Standard deviation	1.05	1.06	1.07
Range	1–7	1–8	1–8
Chasers[b]			
Average	0.10	0.97	0.52
Standard deviation	0.31	0.18	0.50
Range	0–1	0–1	0–1
Skidding distance (ft)			
Average	805.67	260.00	540.05
Standard deviation	172.57	126.31	312.59
Range	440–1140	50–540	50–1140
Line (ft)			
Average	31.36	29.57	30.49
Standard deviation	14.80	11.06	13.11
Range	8–64	10–60	8–64
Lang[c]			
Average	0.29	0.47	0.38
Standard deviation	0.68	0.82	0.75
Range	0–3	0–3	0–3
Road[b]			
Average	0.00	0.63	0.31
Standard deviation	0.00	0.49	0.46
Range	0	0–1	0–1

[a]Defined in Glossary 4.
[b]Indicator variable, with a value of 0 or 1.
[c]Indicator variable, with a value of 0–3

The statistics for the significant ($P < 0.05$) independent variables in the regression model are summarized in Table 8. Because the indicator variable *Treatment* was not significant, we conclude that differences in treatment did not affect the predicted skid cycle time at Mill Thin 1.

Mill Thin 2

The average total cycle time was 10.17 min for the only treatment, LTO (Table 5). The largest components of the skidding cycle were “travel in loaded” and “travel out empty”. Delays were 23.0% of the average cycle time; the major delays were “personal”, “planning”, and “discussion” (Figure 6).

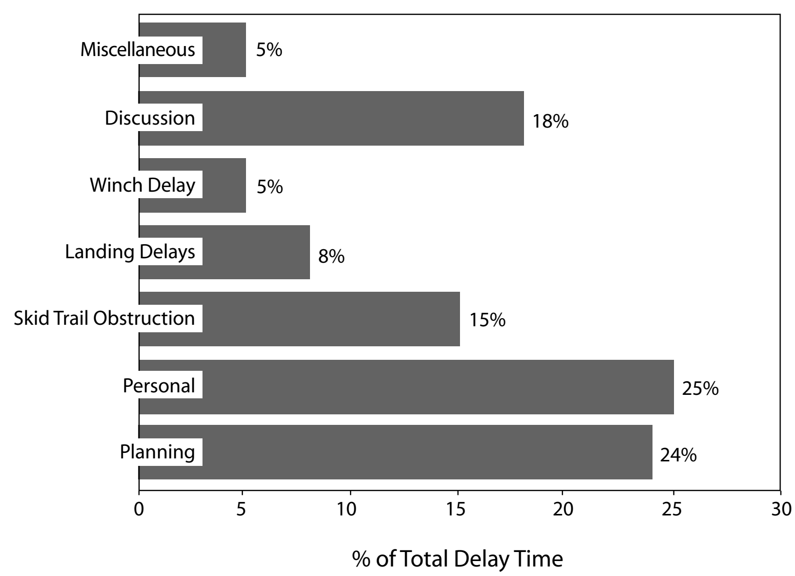

Figure 6. Breakdown of skidding delays from the detailed time study at the Mill Thin 2 site.

The regression model developed from the detailed time studies to predict delay-free skidding cycle time at Mill Thin 2 was

Skid time (min/cycle) = 4.199 + 0.006 *Skidding distance* (ft) + 2.077 *Damage* (no.)
+ 0.143 *Off* (0.5 vehicle lengths) [5]

(adjusted R^2 = 61.4%; standard error = 1.22; sample size = 78 turns)

where all variables are as defined in Glossary 4.

Statistics for the significant ($P < 0.05$) variables of the regression equation are summarized in Table 9.

Table 9. Summary statistics for significant independent variables in the skidding regression equation for Mill Thin 2 [Eq. 5] in the light thin between openings (LTO) treatment.

Variable[a]	Treatment LTO $n = 78$
Skidding distance (ft)	
Average	494.17
Standard deviation	211.52
Range	125–870
Damage (no.)	
Average	0.03
Standard deviation	0.16
Range	0–1
Off (0.5 vehicle lengths)	
Average	2.95
Standard deviation	4.70
Range	0–20

[a]Defined in Glossary 4.

Tap Thin

The average total cycle time was 13.93 min over both treatments (Table 7). The three components requiring the most time were "travel out empty", "travel in loaded", and "winch out". Skidding delays were 21.5% of the average total cycle time; the top three delays were "discussion", "skid trail obstruction", and "miscellaneous" (Figure 7).

The regression model developed from the detailed time studies to predict delay-free skidding cycle time was

Skid time (min/cycle) = 5.255 + 2.322 *Treatment* (0–1) + 1.117 *Tops* (no.) + 0.501 *Logs* (no.) + 0.003 *Skidding distance* (ft) - 0.641 *Favor* (0–1) - 1.010 *Road* (0–1) [6]

(Adjusted R^2 = 75.1%; standard error = 1.31; sample size = 146 turns)

where all variables are as defined in Glossary 4.

Statistics for the significant ($P < 0.05$) variables in the regression equation are summarized in Table 10. The indicator variable *Treatment* proved significant. We therefore conclude that the treatment difference was a useful predictor in determining delay-free skidding cycle time at Tap Thin.

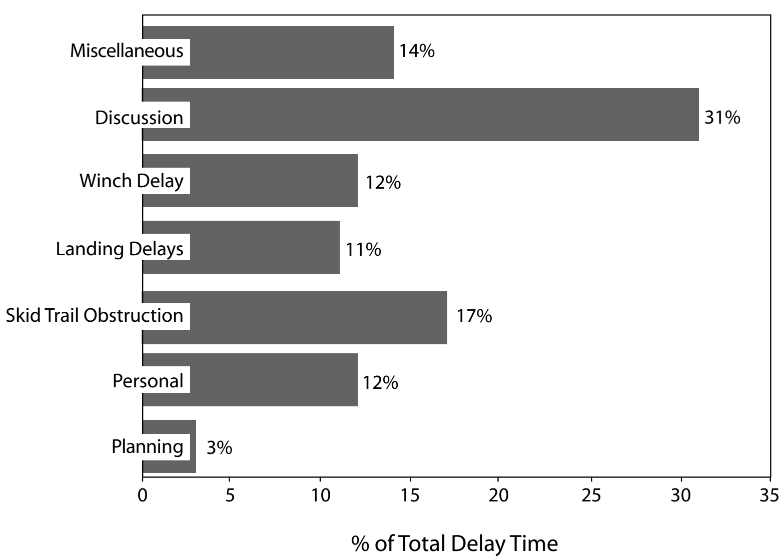

Figure 7. Breakdown of small skidding delays (<10 min) at the Tap Thin site.

Harvesting Costs

Felling

All Sites

Felling costs ranged from \$7.20/CCF at Mill Thin 2 to \$17.73/CCF for the LT at Mill Thin 1 (Table 11). Two aspects controlled the differences in felling costs per unit volume between sites: predicted delay-free cycle time and volume/tree. Across all site/treatment combinations, felling costs increased as delay-free felling cycle time increased. Volume/tree was very similar at Mill Thin 1 and Tap Thin but much higher at Mill Thin 2 (Table 11). It is reasonable that this larger volume/tree difference is attributable to treatment type, i.e., felling all trees in the openings (LTO) created a larger average size. This difference, combined with the lowest delay-free cycle time, yielded a much lower felling cost at Mill Thin 2. Mill Thin 2 also had the lowest average time for the "travel and preparation" felling cycle element (Table 3). It is reasonable to conclude that operating in the openings at Mill Thin 2 increased efficiency and lowered felling costs.

Table 10. Summary statistics for significant independent variables in the skidding regression equation for Tap Thin [Eq. 6] in the light thin (LT), heavy thin (HT), and all treatments.

	Treatment		
Variable[a]	LT $n = 76$	HT $n = 70$	Both $n = 146$
Treatment[b]			
Average	0	1	0.48
Standard deviation	0	0	0.50
Range	0	NA	0–1
Tops (no.)			
Average	0.14	0.14	0.14
Standard deviation	0.58	0.35	0.48
Range	0–4	0–1	0–4
Logs (no.)			
Average	5.05	4.71	4.89
Standard deviation	0.86	0.80	0.85
Range	2–8	2–6	2–8
Skidding distance (ft)			
Average	583.09	836.51	704.60
Standard deviation	196.01	607.78	460.21
Range	235–895	90–1730	90–1730
Favor[b]			
Average	0.38	0.63	0.50
Standard deviation	0.49	0.49	0.50
Range	0–1	0–1	0–1
Road[b]			
Average	0.22	0.14	0.18
Standard deviation	0.42	0.35	0.39
Range	0–1	0–1	0–1

[a]Defined in Glossary 4.

[b]Indicator variable, with a value of 0 or 1.

NA: not applicable

Individual Sites

At Mill Thin 1, felling costs were 25.8% less for the HT treatment than for the LT (Table 11). The primary factor in determining this difference was the predicted delay-free cycle time. The considerably shorter cycle time of the HT treatment allowed more trees/hr to be felled and thus increased productivity. The difference in predicted cycle time is explained by the significance of the treatment variable, which in turn was driven by the reduction in travel time from one tree to the next at the HT (52% less than in the LT) and the difference in tpa removed (Table 2).

At both Mill Thin 2 and Tap Thin, data were collected only for one treatment. Felling costs for the LTO treatment at Mill Thin 2 averaged \$7.20/CCF. This result is mostly due to the large average tree size, as discussed above. Felling costs for the LT treatment at Tap Thin (145 tpa removed) were similar to those for the HT at Mill Thin 1 (142 tpa removed) (Table 11).

Table 11. Felling productivity rates and costs in the light thin (LT), heavy thin (HT), and both treatments at Mill Thin 1, the light thin with openings (LTO) treatment at Mill Thin 2, and the LT treatment at Tap Thin.

Site	Treatment	Effective hour (min/hr)	Predicted delay-free cycle time[a] (min/tree)	Volume/tree (CCF/tree)	Productivity[b] (CCF/hr)	Felling costs[c] (\$/CCF)
Mill Thin 1	Both	40.92	4.61	0.26	2.30	16.28
	LT	40.92	4.96	0.26	2.11	17.73
	HT	40.92	3.79	0.26	2.84	13.16
Mill Thin 2	LTO	32.40	2.50	0.40	5.20	7.20
Tap Thin	LT	38.40	3.06	0.24	3.00	12.48

[a]From regression equation.

[b]Net scale volume; includes all delay time.

[c]Owning, operating, and labor cost was \$37.02 at all sites.

Skidding and Loading

All sites

Skidding and loading costs ranged from \$15.42/CCF at Mill Thin 2 to \$38.69/CCF for the HT at Tap Thin (Table 12). Two factors primarily controlled the range of skidding and loading costs between sites: skidding distance and volume/log. The greater skidding distance at Tap Thin (Tables 8–10) and resulting increase in total travel time ("travel out empty" + "travel in loaded", Table 7) accounted for most of the delay-free cycle time difference among the sites.

Volume per log also was a driver in determining skidding and loading costs. In each case, skidding and loading cost was inversely related to log volume. Log volume was highest at the lowest cost site (Mill Thin 2) and lowest at the highest cost site (Tap Thin) (Table 12).

Individual sites

At Mill Thin 1, the HT treatment was 31.0% more costly than the LT (Table 12). The difference can mostly be explained by the 20.7% difference in machine costs (Table 12; Appendix, Table A2). Costs for landing equipment and personnel were included in skidder cost calculations for one "loading and skidding" cost. Using three skidders made the total machine cost per hour at LT less than that at HT. The delay-free cycle time from the regression equation for skidding productivity was the same for both treatments at Mill Thin 1. The only other factor contributing to the different costs is the volume per turn of the two treatments (Table 12), driven by the significant difference of number of logs per turn (Table 6).

At Mill Thin 2, skidding and loading cost on the LTO treatment averaged \$15.42/CCF. The controlling influence at Mill Thin 2 seemed to be volume/turn, which is driven by volume/log and logs/turn. Here the difference was in volume/log; Mill Thin 2 averaged the highest volume per log of any site (Table 12), and logs/turn for Mill Thin 2 (4.27) was a median value of the sites (Mill Thin 1, 4.01; Tap Thin, 4.89).

Skidding and loading cost at Tap Thin averaged 32.6% higher in the HT treatment than in the LT (Table 12). The treatments differed statistically, and machine operating costs were the same for both treatments. Thus, the harvesting cost difference between treatments is meaningful and is attributable to differences in treatment. Because treatment was used as an indicator variable, it was difficult to pinpoint specific controls, but cycle times were affected by the treatment unit of origin for each turn.

Skidding distance differences accounted for some of the difference as well. Although the overall percentage of skidding cycle time at Tap Thin for travel ("travel out empty" and "travel out loaded") was similar to that at Mill Thin 1 and Mill Thin 2, the actual time consumed in these two activities was significantly more at Tap Thin (Table 7). This difference alone is responsible for the large difference of skidding and loading costs at Tap Thin. The use of swing roads, instead of new road construction, exaggerated average skidding distance here. The impact of skidding distance on cost is discussed further in the "Standardization" section, below.

Table 12. Skidding productivity rates and costs in the light thin (LT), heavy thin (HT), and both treatments at Mill Thin 1 and Tap Thin and the light thin with openings (LTO) treatment at Mill Thin 2.

Site	Treatment	Effective hour (min/hr)	Predicted delay-free cycle time[a] (min/tree)	Volume CCF/turn	Volume CCF/log	Productivity rate (CCF/hr)	Machine cost[b] (\$/hr)	Skid and load (\$/CCF)
Mill Thin 1	Both	50.94	7.47	0.61	0.153	4.18	86.55	21.68
	LT	50.94	7.47	0.64		4.37	78.44[c]	18.91
	HT	50.94	7.47	0.58		3.98	94.66[d]	24.78
Mill Thin 2	LTO	46.20	7.65	0.89	0.209	5.39	78.14[e]	15.42
Tap Thin	Both	47.10	10.59	0.66	0.134	2.92	94.58	33.55
	LT	47.10	9.47	0.68		3.36	94.58[d]	29.17
	HT	47.10	11.79	0.63		2.52	94.58[f]	38.69

[a]From regression equation.

[b]Own, operate, labor; includes 40% fringe benefits.

[c]Loader and chaser costs were divided by three (three tractors were used).

[d]Loader and chaser costs were divided by two (half the costs were shared with another operation offsite).

eSelf loader @\$60/hr; pro-rated to 2 hr/day of loading (2 truck loads–shift level) = \$12/hr.

[f]Loader and chaser costs were divided by two (two tractors were used).

Total Harvesting Costs

Total harvesting costs (stump to truck) ranged from a low of \$23.40/CCF at Mill Thin 2 to a high of \$46.81/CCF at Tap Thin (Table 13). An average of \$0.78/CCF was determined for move-in/out costs at all sites.

Table 13. Total harvesting costs ($/CCF) in the light thin (LT), heavy thin (HT), and both treatments at Mill Thin 1 and Tap Thin and the light thin with openings (LTO) treatment at Mill Thin.

Site	Treatment	Felling	Skidding & loading	Move in/ Move out	Stump to truck
Mill Thin 1	Both	16.28	21.68	0.78	38.74
	LT	17.73	18.91	0.78	37.42
	HT	13.16	24.78	0.78	38.72
Mill Thin 2	LTO	7.20	15.42	0.78	23.40
Tap Thin	Both	12.48	33.55	0.78	46.81
	LT	12.48	29.17	0.78	42.43
	HT	--	38.69	0.78	--

At Mill Thin 1, the HT treatment cost 3.5% more than the LT (Table 13), which offset the lower felling cost of the HT treatment and made stump-to-truck costs of the two treatments nearly the same. The LTO treatment at Mill Thin 2 averaged $23.40/CCF stump to truck. This site also had the lowest cost components for felling and for skidding and loading of any site/treatment combination. The LT total harvesting costs at Tap Thin were the highest of any site/treatment combination. Had the felling data been collected, the HT would have had the highest stump-to-truck cost, considering that skidding and loading alone cost $38.69/CCF. As discussed above, the use of tractor swing roads significantly increased the average skidding distance at Tap Thin and resulted in higher skidding and loading costs than at other sites.

Standardization

Comparing sites and treatments across sites in this study was difficult. Mill Thin 2 had only the LTO treatment, which was not duplicated at the other sites. Further, felling data were not collected for the HT at Tap Thin. The only site/treatment combinations that can be compared are the LTs at Map Thin 1 and Tap Thin. Even here, differences in initial stocking levels and volume harvested in stands (Table 2) make intersite comparisons difficult. Standardizing portions of the data, however, provides a better idea of the factors controlling productivity and costs without drawing specific site/treatment comparisons.

To compare costs more evenly across the sites, we used standardized values (550 ft skid distance, 0.160 CCF/log) to eliminate the differences in skidding distance and CCF/log. These variables exerted the most control on cost sensitivity and did not result from treatment differences.

Dividing the effective hour by the predicted delay-free time, we calculated that 8.9 trees/hr were felled at Mill Thin 1, 113.0 trees/hr at Mill Thin 2, and 12.6 trees/hr at Tap Thin. Standardizing the average number of limbs cut per tree in the regression equation for each site to 30.0 showed a similar, though less dramatic, trend for felling productivity across sites: 13.1 trees/hr at Mill Thin 2, 11.6 trees/hr at Tap Thin, and 10.8 trees/hr at Mill Thin 1. Felling efficiency may have been influenced by differing amounts of experience within felling crews, the subcontracting of felling at Mill Thin 2 and Tap Thin, or both.

Table 14. Standardized felling, skidding and loading, and stump to truck cost figures ($/CCF) for each site/treatment combination.

Site	Treatment	Felling	Skidding & loading	Move in/ Move out	Stump to truck
Mill Thin 1	Both	15.57	20.09	0.78	36.44
	LT	16.95	17.43	0.78	35.16
	HT	12.59	23.07	0.78	36.44
Mill Thin 2	LTO	9.40	19.96	0.78	30.14
Tap Thin	All	10.45	26.24	0.78	37.47
	LT	10.45	22.62	0.78	33.85
	HT	--	30.50	0.78	--

Volume per log affected both felling and skidding costs, whereas skidding distance affected only skidding costs. Table 14 shows costs with skidding distance for each site standardized to 550 ft and volume/log standardized to 0.16 CCF for both felling and skidding.

Mill Thin 1 costs were hardly affected by standardization. The standard values used were close to the actual average values of Mill Thin 1 (Tables 8, 12), so one would not expect much difference. The significant treatment difference for felling held for costs (Table 12). The difference in skidding costs is related to the difference of operating costs per hour, as discussed earlier.

In contrast, standardization increased the cost of Mill Thin 2 to $30.14/CCF, a 28.8% increase. This site had both the lowest average skidding distance (Table 9) and the largest log volume (Table 12). Of the $6.74/CCF stump-to-truck increase, the felling differential accounted for $2.20/CCF and the skidding component, $4.54/CCF.

The same standards reduced the stump-to-truck costs for the LT at Tap Thin substantially, by 20.2% (Table 9). Since the lowest volume/log and the highest average skidding distance were at Tap Thin, it is reasonable that increasing CCF/log and decreasing the average skidding distance would lower the stump-to-truck costs at Tap Thin. The significant effect of treatment shows its influence on skidding and loading costs here (Table 12). The cost figures for Tap Thin are similar to those at Mill Thin 1 and Mill Thin 2 when skidding distance is standardized.

Sensitivity of log volume and skidding distance on productivity

The regression model and actual volume per log for each site were used to generate information on sensitivity of productivity rate to increased skidding distance (Figure 8). In all cases, productivity decreased as skidding distance increased. The productivity at Mill Thin 2 seemed to have the most potential to be affected by skidding distance increases.

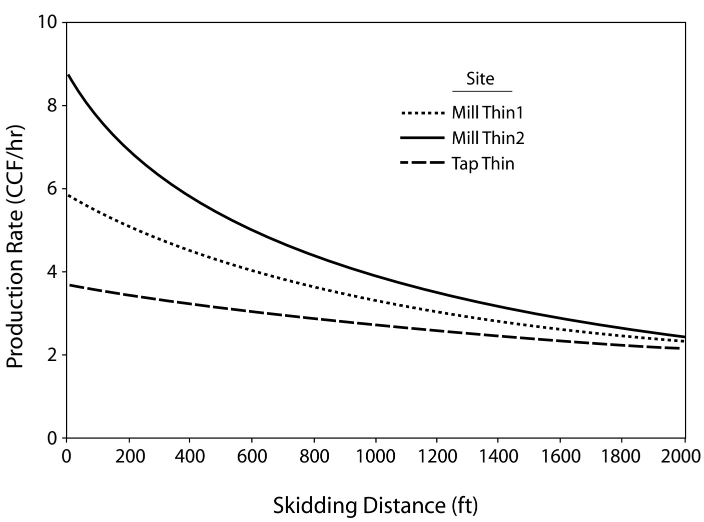

Figure 8. Skidding productivity rate by skidding distance for each site.

Volume per log (CCF/log) can also have a major impact on skidding productivity (Figure 9). A skidding distance standard of 550 ft was used in the regression equation for each site. All sites responded similarly to the increase in log volume.

To show the interaction effect of skidding distance and log volume on skidding and loading cost, we chose Mill Thin 1 as an example. Both skidding distance and log volumes affected skidding costs (Figure 10). As log volumes increased, costs were less affected by skidding distance increases. This figure also shows the dramatic effect of very small logs (<0.15 CCF/log) on production costs at various skidding distances.

Discussion

Although initial site differences and irregularity of silvicultural prescriptions made specific site/treatment comparisons difficult, some interesting observations are possible.

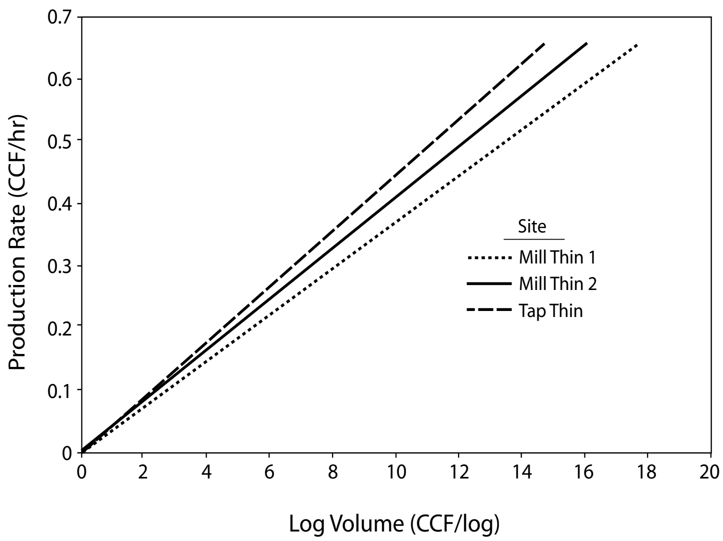

Figure 9. Effect of log volume on skidding productivity rate.

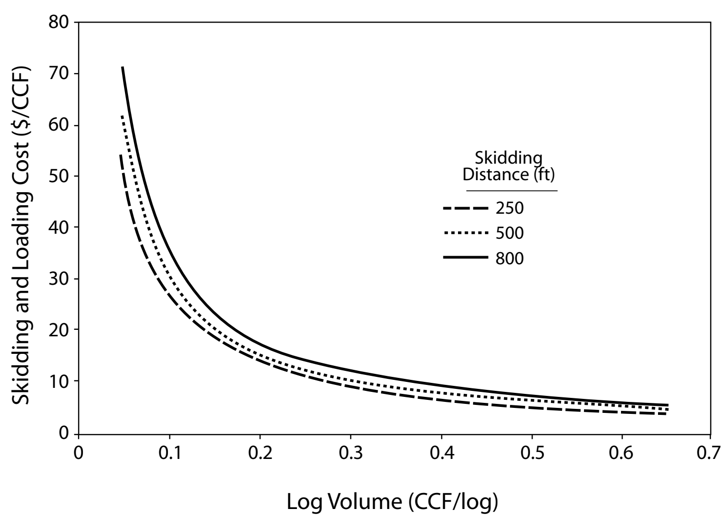

Figure 10. Relative effect on cost as skidding distances and log volumes increase (Mill Thin 1).

Felling

The largest component of the felling cycle time at each site was "limb and measure", accounting for no less than 26.3% of the time (Table 3). All other felling cycle components required similar relative percentages of time across all sites. The time allotted for "limb and measure" alone at Mill Thin 1 was longer than the total delay-free cycle time at Mill Thin 2 and almost as long as the delay-free time at Tap Thin. The difference in the time required for "limb and measure" at each site accounted for the majority of the difference in the actual delay-free cycle times of each site. "Limb and measure" required 1.56 min longer at Mill Thin 1 and 0.63 min longer at Tap Thin than it did at Mill Thin 2; delay-free cycle time was 2.06 min longer at Mill Thin 1 and 0.55 min longer at Tap Thin. Number of limbs cut drove these results. Mill Thin 1 averaged 72.8 limbs cut per tree, by far the highest total of any site (Table 4).

Skidding and Loading

There is little doubt that skidding distance significantly affected skid cycle time and, therefore, production rate. At each site, "travel out empty" and "travel in loaded" collectively dominated the cycle time (Table 7). The only other component that required a significant percentage of time (>10%) at all sites was "winch-out", which was actually the most time-consuming component at Mill Thin 1.

Interestingly, skidding and loading costs at Mill Thin 1 were higher for the HT than the LT (Table 12), although the LT skidding distance average was more than three times greater (Table 6). Our methodology used one regression equation per site, not per treatment, to determine delay-free cycle times, with treatment as an indicator variable. Since treatment was not significant and the equation used the same value for skidding distance (the average value of the site, 540.05 ft), the predicted delay-free cycle time used for cost calculations was the same for each treatment. The drastic difference in skidding distance between treatments at Mill Thin 1 was somewhat obscured by this methodology. In contrast is the cost difference at Tap Thin, where average skid distance at LT was 69.7% of that at HT (Table 10). The significance of the treatment variable at Tap Thin led to a different predicted delay-free cycle time for each treatment, showing the influence of skidding distance on cost and productivity. Costs for LT and HT at Mill Thin 1 were different (Table 12), but the difference was related more to operating cost per hour and volume/turn.

Although machine costs for skidding and loading varied by site, only Mill Thin 1 had different machine costs per hour between treatments. Since this study made no specific comparisons across sites, the difference in operating costs among sites was not evaluated further. The operating cost difference at Mill Thin 1, however, warrants some exploration.

Total harvesting costs at Mill Thin 1 were relatively similar between treatments. The HT treatment however, was more cost efficient in regard to felling costs, whereas the LT treatment was more cost efficient in regard to skidding and loading costs. Felling costs were truly comparable, since both treatments were operating based on the same cost structure. The cost of skidding and loading for each treatment, however, was quite different. The difference in skidding cost per unit volume is somewhat exaggerated by the different machine costs associated with each treatment, determined by the equipment spread of separate logging contractors.

The key is the productivity rates of each treatment. For felling, the HT had the higher productivity (Table 11), and thus the lower cost per unit volume. For skidding and loading, the LT had the higher productivity (Table 12), and the lower cost per unit volume. With similar operating techniques, and thus operating costs per hour, the LT still would have been more cost efficient because of the higher productivity rate, but the difference in skidding and loading costs per unit volume would have been less, specifically $1.76/CCF vs. $5.87/CCF (using the LT operating costs as a standard). In other words, in looking at total harvesting costs at Mill Thin 1, one could reduce the HT treatment by $4.11/CCF for a more fair comparison between treatments. The difference in cost after such comparison is solely reflected by the productivity rate, driven in the calculation by logs/turn, for each treatment. Using similar skidding and loading operating costs among treatments would provide a total harvesting cost of $34.61/CCF for the HT, 7.5% lower than the $37.42/CCF for the LT. With this reasoning, the HT treatment appears more cost efficient from stump to truck than does the LT. This result is reasonable, since tpa removed and volume harvested were both highest in the HT treatment.

Summary

Productivity and costs of crawler tractor harvesting systems were evaluated for three silvicultural prescription applications. Comparisons across sites were not possible because treatments were not replicated at each site and preexisting stand conditions differed among sites. Because treatments were defined as part of a larger multidisciplinary study, this analysis could not define treatment definitions. Treatments were defined for the overall study by residual tpa and not by the portion of the stand removed. As a result, the same treatment had inconsistent outcomes, in terms of tpa removed or volume removed, across sites. Stand conditions and environmental factors, however, provided an opportunity to examine variations in key variables and operating practices of the harvesting contractor. In that vein, this paper focuses on harvesting costs

of different silvicultural regimes without drawing firm comparisons or conclusions about cost effects of treatments across sites.

At all sites, felling productivity and costs were most influenced by the amount of time spent delimbing and, more directly, by the number of limbs removed per tree. In all cases, delimbing was the most time-consuming component of the felling cycle. This could indicate the need to mechanize delimbing in these operations.

The independent variables common to regression equations to determine delay-free felling cycle time at all sites were DBH, number of cuts, and number of limbs cut. The only treatment comparison possible at any site showed that felling in the LT treatment cost more than in the HT at Mill Thin 1. With one exception, treatment felling costs decreased per unit volume as tpa removed increased. In the LTO at Mill Thin 2, the much lower percentage of cycle time spent delimbing than at either Mill Thin 1 or Tap Thin offset the lower tpa removed value.

Across sites, the average skidding distance controlled productivity and costs more than any other factor. This was evidenced most by the fact that the travel components of the skidding cycle, "travel out empty" and "travel in loaded", required the most time at each site.

"Skidding distance" was the only independent variable that appeared in every regression model for predicting delay-free skidding cycle times. Treatment differences were significant only at Tap Thin. In cases such as Mill Thin 1, however, where treatment differences of a dominant variable were large, use of treatment as an indicator variable seemed to obscure real information when that equation was used to predict costs of different treatments.

The interactions of skidding and loading costs across sites and within sites were somewhat complicated due to extraneous factors, such as differing operating costs resulting from different equipment spreads and large discrepancies in volume per log. In general, though, skidding and loading costs increased as skidding distances increased.

Total harvesting cost is simply the sum of the felling, the skidding and loading, and the move in/out costs (held constant at all site/treatment combinations). Therefore, the drivers of those individual cost components also drive total harvesting costs. It is apparent from this study that, independent of treatment, certain sites cost more to harvest than others. Factors influencing total harvesting cost at each site include tpa removed, limbiness of timber, average skidding distance, and volume per log.

In general, this study indicated that logging costs per unit volume decreased under any of the following conditions: tpa removed increased, number of limbs decreased, average skidding distance decreased, or volume per log increased. As expected, treatments removing the most tpa and the highest total volume per acre generally resulted in a lower total harvesting cost per unit, shown best by comparing the cost differences of the HT and LT treatments. When the regression equation was used to model similar operating conditions and costs, total harvesting cost of the HT treatment was lower than that of the LT. A silvicultural treatment that favors one of the above conditions over another could lower logging costs.

Although this study does not allow firm conclusions on cost differences between treatments, the results do reinforce the basic cost controls of forest harvesting: the interaction of skid distances and removal volumes on harvest productivity and costs. It is imperative that unit layout minimize skid trail distances, especially when activities involve removal of smaller trees and relatively low volumes. It is important for forest managers to take these factors into account when considering alternative silvicultural management regimes that entail harvesting in young stands.

Literature Cited

Allen, MM. 1997. *Soil Compaction and Disturbance Following Thinning of Second Growth Douglas-fir with a Cut-to-length system and a Skyline System in the Oregon Cascades.* MF paper, Department of Forest Engineering, College of Forestry, Oregon State University, Corvallis.

Bennett, DM. 1993. *Partial Cutting in a Second Growth Douglas-fir Stand in Coastal British Columbia: Productivity, Cost, and Soil Impacts.* Technical Note TN-199, FERIC, Pointe-Claire, QC, Canada.

Danish Institute of Forest Technology. 1988. *SIWORK3 version 1.1*. Frederiksberg, Denmark.

Garland, JJ. 1983. Designated skid trails minimize soil compaction. *The Woodland Workbook: Logging. Extension Circular 1110*. Oregon State University Extension Service; Corvallis.

Han, H-S. 1997. *Damage to Young Douglas-fir Stands from Commercial Thinning with Various Timber Harvesting Systems and Silvicultural Prescriptions: Characteristics, Sampling Strategy for Assessment of Future Loss.* PhD dissertation, Department of Forest Engineering, College of Forestry, Oregon State University, Corvallis.

Han, H-S, and LD Kellogg. 1997. Comparison of damage characteristics to young Douglas-fir stands from commercial thinning using four timber harvesting systems, pp. 76–85 in *Proceedings of the 1997 Annual COFE meeting*, Rapid City, SD. Council of Forest Engineering, Corvallis OR.

Hayes, JP, SS Chan, WH Emmingham, JC Tappeiner, LD Kellogg, and JD Bailey. 1997. Wildlife response to thinning young forests in the Pacific Northwest. *Journal of Forestry* 95: 28–33.

Kaiser, FC 1997. United States forests and timber supplies in the 21st century. *Commonwealth Forestry Review* 76(1): 25–30.

Kellogg, LD, P Bettinger, and RM Edwards. 1996a. A comparison of logging planning, felling, and skyline yarding costs between clearcutting and five group-selection harvesting methods. *Western Journal of Applied Forestry* 11: 90–96.

Kellogg, LD, ME Miller, and ED Olsen. 1999. *Skyline Thinning and Production and Costs: Experience from the Willamette Young Stand Project.* Research Contribution 21, Forest Research Laboratory, Oregon State University, Corvallis.

Kellogg, LD, GV Milota, and M Miller, Jr. 1996b. A comparison of skyline harvesting costs for alternative commercial thinning prescriptions. *Journal of Forest Engineering* 7(3): 7–23.

Kellogg, LD, GV Milota, and B Stringham. 1997. *Logging Planning and Layout Costs for Thinning: Experience from the Willamette Young Stand Project.* Research Contribution 20, Forest Research Laboratory, Oregon State University, Corvallis.

Kellogg, LD, and BD Spong. 2004. *Cut-to-Length Thinning Production and Costs: Experience from the Willamette Young Stand Project.* Research Contribution 47, Forest Research Laboratory, Oregon State University, Corvallis.

Klepac, J, SE Reutebuch, and RB Rummer. 1999. An assessment of soil disturbance from five harvesting intensities, Paper No. 99-5052 in *Proceedings of the 1999 ASAE Annual International Meeting*, Toronto, ON.

Sessions, J, and JB Sessions. 1986. *PACE—The Productivity and Cost Evaluation Program.* Department of Forest Engineering, College of Forestry, Oregon State University, Corvallis.

Appendix. Logging Costs: Appraisal Tables

Table A1. Tractor-felling costs ($/hr) for all sales in the Willamette Young Stand Study.

Item	Ownership	Operating	Labor	Total
Stihl 044 with 28-in. bar	0.27	1.31	31.36	32.94
Used backup saw	0.18	0.00	0.00	0.18
Chevrolet ¾ ton 4 x 4	1.76	1.68	0.00	3.44
Miscellaneous supplies	0.46	0.00	0.00	0.46
Total felling cost for one cutter				**37.02**

Table A2. Tractor logging costs ($/hr) in the Mill Thin I sale, Willamette Young Stand Study.

Item	Ownership	Operating	Labor	**Total**[a]	HT[b]	LT[c]
Case 550 crawler with winch line	9.94	11.03	25.06	**46.02**	46.02	46.02
Chaser	0.00	0.00	23.30	**23.30**	11.65	7.76
Chevrolet crew-cab pickup 4 x 4	2.76	2.09	0.00	**4.85**	2.42	1.61
Used 1500-gallon fire truck	0.41	0.08	0.00	**0.49**	0.25	0.16
Case 125B Tract-Mount loader	22.79	12.38	26.74	**61.91**	30.95	20.64
Chevrolet extended-cab pickup 4 x 4	2.89	1.84	0.00	**4.73**	2.36	1.58
Landing supplies				**2.00**	1.00	0.67
Total cost/hr						
Skidding				**76.66**	**61.34**	**56.22**
Loading				**66.64**	**33.32**	**22.22**
Skidding and loading				**143.30**	**94.66**	**78.44**

[a]Costs calculated for 1 tractor only.
[b]Costs calculated for 1 tractor. The cost of the chaser and loader was halved because of work done on an offsite operation.
[c]Costs for 3 tractors.

Table A3. Tractor logging costs ($/hr) in the Mill Thin II sale, Willamette Young Stand Study.

Item	Ownership	Operating	Labor	**Total**[a]	Prorated[b]
Case 850G crawler with winch line	12.55	13.21	25.06	**50.82**	50.82
Chaser	0.00	0.00	23.30	**23.30**	11.65
Chevrolet crew cab pickup 4 x 4	2.76	2.09	0.00	**4.85**	2.42
Used 1500-gal fire truck	0.41	0.08	0.00	**0.49**	0.25
Self-loader log truck			60.00	**60.00**	12.00
Landing supplies				**2.00**	1.00
Total cost/hr					
Skidding				**81.46**	**66.14**
Loading				**60.00**	**12.00**
Skidding and loading				**141.46**	**78.14**

[a]Cost charged to one machine with self-loader on landing 100%.

[b]Cost charged to two machines with self-loader on landing 2 hr/day or 20 min/hr, based on 10-hr workday.

Self-loaders charged $60/hr

1 hr loading time + 2 hr highway time, for total of 3 hr for complete cycle

*Costs are divided by ½ to share the costs of the operation per machine.

Table A4. Tractor logging costs ($/hr) in the Tap Thin sale, Willamette Young Stand Study.

Item	Ownership	Operating	Labor	Total[a]	Prorated[b]
John Deere 550 crawler with winch line	11.34	10.91	25.06	**47.31**	47.31
Chaser	0.00	0.00	23.30	**23.30**	11.65
Chevrolet crew cab pickup 4 x 4	2.76	2.09	0.00	**4.85**	2.42
Used 1500-gal fire truck	0.41	0.08	0.00	**0.49**	0.25
Koehring 6630 Tract-Mount loader	24.32	12.74	26.74	**63.80**	31.95
Landing supplies				**2.00**	1.00
Total cost/hr					
Skidding				**77.95**	**62.63**
Loading				**63.80**	**31.95**
Skidding and loading				**141.75**	**94.58**

[a]Costs for 1 machine

[b]Costs for 1 machine and ½ loader costs

NOTE: The HT treatment used two machines, with one chaser and loader. The LT treatment used one machine, but shared the cost of a chaser and loader with an off-site operation. Thus, the skidding and loading cost per machine was the same for the HT and LT treatments.

OSU
Oregon State
UNIVERSITY

Forestry Communications Group
Oregon State University
256 Peavy Hall
Corvallis, OR 97331-5704

Address Service Requested

Non-Profit Org.
U.S. Postage
PAID
Corvallis, OR
Permit No. 200