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Comparison of Damage Characteristics to Young Douglas Fir Stands from Commercial Thinning Using Four Timber Harvesting Systems

Han-Sup Han

and

Loren D. Kellogg
Oregon State University
Corvallis, Oregon, USA

ABSTRACT: Each harvesting system leaves its own type of damage to crop trees during thinning operations. Understanding the impact of different harvesting systems helps forest managers to achieve management objectives associated with sustainability and quality control. Damage to residual trees from commercial thinning was characterized and compared with four common harvesting systems in western Oregon: tractor, cut-to-length, skyline and helicopter. This study was conducted in six young (30 - 50 years old) Douglas-fir (*Pseudotsuga menziesii*) stands having various residual densities. Scarring by ground-based systems was more severe: scar sizes were bigger, and gouge and root damage was more prevalent than that caused by skyline and helicopter systems. Crown removal and broken-top damage was more common with skyline and helicopter logging. The damage levels varied among different thinning treatments and logging systems. The levels were heavily influenced by many compounding factors. In the cut-to-length system, the harvester caused more wounding to crop trees than the forwarder, but forwarder scars were larger and sustained severe gouge damages.

KEY WORDS: logging damage, commercial thinning, harvesting systems

INTRODUCTION

Intensive forest management practices in western Oregon increasingly require the use of thinning prescriptions for both private and public land. Sessions *et al.* (1991) surveyed the use of thinning practices in western Oregon. Managers responsible for industrial forests indicated that within 25 years, current management intensities would require thinning on about two thirds of their forest lands. For public lands in the same survey, the Forest Service and Bureau of Land Management (BLM) planed to implement intensive management on virtually all of their forested acres allocated to timber production in western Oregon. Under their 10-decade management plan which began in 1991, the area to be thinned was projected to increase by five times over the 10-decade period.

These trends are the same in Washington State. McNeel *et al.* (1996) surveyed forest land managers in western Washington and found that public land owners have increased the acreage thinned on their managed lands by almost 200% in the past 5 years.

During fiscal year 1995, the Oregon Department of Forestry estimated that 627,668 acres of forest land had merchantable logs removed from them. Partial cut and clear cut areas were 524,701 acres (84%) and 102,967 acres (16%) respectively. Partial cuts include shelterwood, seed tree, selective, preparation, intermediate, improvement, and salvage cuts.

Since any type of damage to remaining trees is a by-product of thinning operations, it is of interest to forest managers and researchers. The understanding of logging impacts to residual stands is more important than ever to ensure the sustainablity and quality control of future stands.

Lanford and Stokes (1995) compared two thinning systems on logging damage to 18-year-old loblolly pine trees. They reported that the feller-buncher/ skidder system scarred significantly more trees, 62 trees per ha (tph, 25 trees per acre (tpa)) than did the cut-to-length system, 25 tph (10 tpa). Compared to the cut-to-length system, the skidder system had 10 times larger scars and 24 times more scar area per acre.

A residual stand damage study of a cut-to-length system in the Pacific Northwest was conducted by Bettinger and Kellogg (1993). They found 39.8% of Douglas-fir trees sustained some damage with only 0.8% of trees sustaining major damage. The majority of logging damage was relatively small. Total scar area per acre was 1.2 m^2 (12.85 ft^2), which was far greater than Lanford and Stokes's observation, 0.046 m^2 (0.5 ft^2). They also noted that most of the damage occurred within 4.6 m (15 ft) of a trail centerline and originated within 0.9 m (3 ft) of the ground line.

Aho *et al.* (1983) compared the amount of damage from commercially thinned, young-growth stands of true fir, Douglas-fir, and ponderosa pine with two logging methods: conventional logging practices and logging procedures designed to reduce damage to residual trees. In the five conventionally thinned young-growth stands surveyed in northern California, 22% to 50% of the residual trees were wounded. The level of damage in four stands that were thinned using techniques designed to reduce logging skidding injuries were substantially lower, ranging from only 5% to 14%.

Damage to leave trees is less severe with skyline thinning than with conventional skidding or tractor-based operations (Aulerich *et al.* 1976, Carvell 1984, Fairweather 1991). Aulerich *et al.* (1976) reported that 11% of trees after tractor thinning had wounds over 46 cm^2 (7.1 in^2), and 7% of the stems following skyline thinning had wounds of this size. In the tractor thinned unit, 58% of the scars were either on roots or the lower 30 cm (11.8 in) of the tree trunks. Ninety-eight percent of skyline thinning wounds were over 30 cm (11.8 in) above ground, and 22% of these scars were more than 1.52 m (4.6 ft) above ground. In a skyline logging study, Kellogg *et al.* (1986) reported that most yarding damage (66.6% of total scar area) occurred within 6 m (20 feet) of the skyline corridor centerline. They also noted that selective thinning caused greater residual stand damage than a herringbone thinning.

In a commercial thinning using a small helicopter with a payload capacity of 1,133 kg (2,500 pounds), Flatten (1991) found that damage to a young Douglas-fir stand appeared to be far less than typically found with skyline systems.

The questions of a maximum acceptable damage level and what constitutes a damaged tree arise whenever penalties for damage are an issue. Government agencies and private industry have answered these questions in their policies, but they are not consistent. Some of the rules are written with ambiguous language resulting in different interpretation. The minimum scar size to constitute damage varies from agency to agency, ranging from 6.5 cm^2 (1 in^2) to 464 cm^2 (72 in^2) or no written definition. A maximum acceptable damage level consisting of scarring, crown and root damage is also not consistent: 3%, 5% of total damaged tree or an inspector's decision.

Damage to residual trees is related to several factors besides the logging system, including thinning intensity, planning and layout, season of harvest, species, felling patterns, yarder size, skyline deflection, tree distance from skid trails, tree size, tree length being harvested and site conditions (slope, soil texture, rockiness, etc.). However, researchers agree that the most critical factor affecting the damage level is a worker's skill and efforts (McLaughlin and Pulkki 1992, Hoffman 1990; Cline *et al.* 1991; Ostrofsky *et al.* 1986; Kellogg *et al.* 1986).

The results of the first half of this project were presented at the annual Council on Forest Engineering (COFE) meeting last year (Pilkerton *et al.* 1996), which included skyline and helicopter thinning units. In this paper, we compare the characteristics of stand damage in relation to various thinning treatments and to four logging systems including the results from last year (helicopter logging). We also discuss the harvesting variables affecting damage level.

METHODS

Study Sites and Thinning Prescriptions

Data for this study were collected on commercially thinned young stands in the central Cascade Mountains of Oregon. Table 1 describes the characteristics of stands and thinning systems used for the study areas. For the purpose of stand damage comparison, one cable (3 units), one cut-to-length (3 units), and two tractor sales (5 units) were selected on the Willamette National Forest, totaling 210 ha (521 acre). The study areas were administrated by three different Forest Service Ranger Stations. These second-growth stands areas were previously clearcut between the early 1940s and 1950s, broadcast burned soon afterward and allowed 2-4 years to regenerate naturally before being interplanted with Douglas fir. Stands were dominated by Douglas fir with two layers of scattered western hemlock and individual or clumps of big leaf maple (*Acer macrophyllum*).

Table 1. Study areas and stand descriptions before commercial thinning in the Willamette National Forest *.

Sale Name	Logging System	Study Area	Mean Tree Age	Mean Tree DBH	Mean Tree HT	# of Trees	Basal Area	Slope
		ha (ac)	years	cm (in)	m (ft)	/ha (/ac)	m^2/ha (ft^2/ac)	%
Walk Thin	Skyline	57.4 (142)	45	26.4 (10.4)	22 (74)	667 (270)	27 (118)	5 - 80
Mill Thin	Tractor	49.3 (122)	43	30 (11.8)	24 (78)	573 (232)	40 (172)	0 - 15
Tap Thin	Tractor	25 (62)	46	27.4 (10.8)	22 (73)	531 (215)	33 (145)	0 - 40
Flat Thin	Cut-to-length	90.9 (225)	45	28.7 (11.3)	23 (77)	504 (204)	43 (186)	0 - 20

Three thinning treatment units were located on each of the study areas (four replications). Three different residual stand densities after thinning were: (1) heavy thinning (123-136 tph, 50-55 tpa), (2) light thinning (272-297 tph, 110-120 tpa), and (3) light thinning with patch clearcuts (approximately 0.2 ha (1/2 acre)) openings. Trees left uncut were healthy dominant and co-dominant Douglas fir and western hemlock marked by Forest Service crews before thinning. Thinning primarily removed selected commercial value trees from the mid-size diameter classes (18-41 cm (7-16 in)).

Timber Harvesting Systems

Three thinning systems were compared: skyline, tractor, and cut-to-length. The equipment used was small and appropriate for thinning. These timber harvesting systems are commonly used in the Pacific Northwest. Each sale was contracted with different loggers and their thinning experiences varied from less than 6 months to over 10 years.

Skyline logging system: The skyline logging system consisted of chainsaw tree felling, limbing, and bucking, followed by cable yarding. Cable yarding was done using a smallwood yarder, Koller 501 with Eaglet mechanical slackpulling carriage in a shotgun skyline system. Skyline roads were determined and marked before felling by the contractor. Intermediate supports and tailtrees were rigged on 16% and 84% of skyline roads, respectively. Logs were partially suspended. Landing patterns in Walk Thin were mainly fan-shaped (75%) with some parallel skyline roads (25%).

Cut-to-length logging system: The cut-to-length logging system consisted of two pieces of equipment: harvester and forwarder. The harvester was a 2618 Timberjack (tracked carrier) with a South Fork Squirt Boom and a Waterous 762b hydraulic harvesting head. The forwarder was a 1210 Timberjack. A harvester worked on the designated skid trails spaced approximately 20 m (60 feet) apart and completed felling, delimbing, and bucking of the tree into log segments. The harvester cut trees up to 56 cm (22 inches) in diameter but had increasing difficulty with trees over 48-51 cm (19-20 inches). Manual felling was required for some large trees. The forwarder traveled on the designated trails that the harvester passed over and transported the logs to the landing or roadside.

Tractor logging system: The tractor logging system consisted of chainsaw tree felling, limbing, and bucking, followed by skidding with a small crawler tractor or skidder. Trees were directionally felled to facilitate winching and to minimize stand damage. The tractor or skidder was equipped with a winch line so that designated skid trails were spaced approximately 40 m (120 feet) apart. There were three different logging contractors in tractor units; two in Mill Thin and one in Tap Thin. Skidders used in Tap Thin units were John Deere 550 winch line and 540 grapple (rubber tired) while Case 550 and D-5 Cat crawler tractors were used in the Mill Thin units.

Procedure

Damage to residual trees was surveyed during summer of 1996 and spring of 1997 after commercial thinning was completed. Trees in each unit were sampled using fixed circular plots, except for the Heavy thinning in Mill Thin. This unit was only 1 ha (2.5 acres), thus all trees in the unit were checked for logging damage.

The sampling pattern was a systematic grid having the sample units, with a constant distance between sampling units within rows equally spaced. These rows were perpendicular to the primary direction of yarding or skidding to landings. If this was impossible due to fan-shape yarding or skidding patterns, we stratified the unit to avoid locating the rows parallel to skyline roads or skid trails. Plot sizes were 0.04 ha (1/10 acre) for Light thinning treatments or 0.08 ha (1/5 acre) for Heavy thinning treatments. The sample size of each unit was calculated using (Thompson 1995):

$$n_0 = \frac{N * p(1-P)}{(N-1)\left(\frac{d^2}{z^2}\right) + p(1-P)}$$

$$\text{Sample size} = \frac{n_0}{t * p * s}$$

n_0 = number of damaged trees required in sample
N = total number of trees in the unit
p = estimate of percentage damaged trees in unit
d = allowable sampling error, 10% was used.
z = 1.96 for 95% probability
t = number of trees per unit, ha or acre
s = plot size, 0.04 ha (0.1ac) or 0.08 ha (0.2ac)

Once the sample size was calculated, plots were uniformly distributed through the unit. The number of plots ranged from 20 to 27, sampling 2.1% to 34.7% of the area of each unit. In surveying tree damage, we numbered all damaged trees and marked undamaged trees in each plot using paint. This avoided counting the same tree twice or missing trees and facilitated remeasurement if needed.

If a tree was damaged, such as scarring, root and/or crown damage, we measured DBH and collected the data related to tree damage. For scarring damage, scar length, width, and height from the ground level were measured. A scar was defined as removal of the bark and cambial layer, exposing the sapwood. Each scar was traced onto regular paper and these tracings were measured for scar area using a planimeter. If a scar was bigger than the paper size, the scar was traced onto several pieces of paper, measured by piece, and then summed for a total scar area. The scars that could not be reached by hand were measured with Bettinger and Kellogg's method (1993) that uses a camera equipped with a 70 - 210 mm zoom lens. A picture of the scar included a scale, which was mounted on a level rod. Scars were numbered if there were more than one scar per tree.

Scar locations on the bole were noted by four quadrants: (1) quadrant #1 facing the landing, (2) quadrant #2 facing the corridor, (3) quadrant #3 facing the tailtree or tailhold, (4) quadrant #4 opposite to quadrant 2. Each scar was checked to see if the wood fibers were removed, called gouge damage. If a scar had gouge damage, the gouge area and the gouge depth were categorized by three levels: (1) < 25% and < 1 cm, (2) 25% to 50% and 1 cm - 2 cm, (3) > 50% and >2 cm. The distance from the corridor centerline and landing (skyline units only) for every damaged tree was recorded.

If the tree top was removed, it was recorded as a broken-top. Crown damage described when half or more of the crown was removed from the base of the live crown to the top. Any visual scar or severing of the root system was defined as root damage.

To study the wounding caused by the harvester or the forwarder, 3.9 ha (9.7 acres) of the Light thinning unit in the Flat Thin sale was selected. The area included one landing and 5 equipment trails ranging from 365 m (1200 feet) to 669 m (2200 feet) in length. All of the trees in the area were observed for damage after the harvester passed and before the forwarder operation. Paint was sprayed on the wounded area to differentiate the damage created by the forwarder. Every tree in the study area was checked again after the forwarder operation.

RESULTS

Damage Level and Scar Size

The most typical type of damage to the crop trees in every logging system unit was scarring, accounting for more than 90% of the total damage. Crown damage was more prevalent in skyline logging units than in ground based logging systems. Crown removal and broken-tops were caused by lateral excursion of the skyline during lateral inhaul. Ground based systems created more severe root damage than skyline. Root systems below the ground line were easily damaged by repeated passes of equipment and logs being dragged. Skidder blading to level the surface of skid trails also severed root systems. These three types of damage constituted the damage related to thinning operations in this study.

Highest incidence of damage to residual trees was 41.3% in the Light thinning unit of the cut-to-length system (Table 2). The units thinned by the harvester and forwarder sustained higher damage levels (over 30%) than units thinned using a tractor (7.5% to 25.4%) or a skyline system (13.5 to 20.2%). The two lowest damage levels were measured at the Heavy

Table 2. Logging damage levels listed by the minimum size of scars considered as damage.

Sale (logging system)	Thinning Treat-ment	Logging Contractor[a]	Season of Logging	Damage Levels (%) based on the minimum size of scars			
				No Limit	> 155 cm^2 (24 in^2)	> 465 cm^2 (72 in^2)	> 929 cm^2 (144 in^2)
Walk Thin (skyline)	Heavy	A	Winter	18.8	8.3	2.6	1.5
	Light	A	Summer	13.5	5.9	3.8	1.6
	LTw/ patches	A	Summer	20.2	14.6	8.0	5.6
Mill Thin (tractor)	Heavy	B	Summer	25.4	18.7	10.0	4.5
	Light	B	Summer	18.4	9.8	3.9	3.9
	LTw/ patches	C	Summer	9.2	6.6	4.6	3.6
Tap Thin (tractor)	Heavy	D	Summer	7.5	3.3	1.9	1.4
	Light	D	Spring/ Summer	20.2	14.6	8.4	5.1
Flatthin (cut-to-length)	Heavy	E	Winter	34.2	19.2	6.8	4.1
	Light	E	Winter	41.3	14.3	4.7	2.3
	LTw/ patches	E	Summer	31.9	22.2	10.4	6.9

[a] A,B,C,D,E are different logging contractors

thinning unit in Tap Thin, tractor (7.5%) and the Light with patches unit in Mill Thin, tractor (9.2%). Relatively high incidences of logging damage occurred in tractor units, showing 20.2% in the Light thinning unit of Tap Thin and 25.4% in the Heavy thinning unit of Mill Thin. In skyline logging units, damage ratios ranged from 13.5% to 20.2%. No trend in damage incidences by different thinning treatments was observed.

Damage levels sustained during thinning are lower when only considering trees scarred above a minimum scar size (Table 2). For example, only two units, Heavy thinning unit in Mill Thin and Light with patches unit in Flat Thin had a damage level above 10% with scar sizes bigger than 465 cm^2 (72 in^2). When considering the minimum size of scars bigger than 929 cm^2 (144 in^2), all the units sustained logging damage lower than 10%. Damage levels in skyline units dropped significantly to 1.5%, 1.6% and 5.5% for the three thinning treatments.

In the cut-to-length system, the harvester damaged more than twice the number of residual trees than damaged by the forwarder (Table 3). Only 7.6% of the damaged trees were hit by both the harvester and the forwarder. However, the forwarder caused a higher number of scars per tree and bigger scars per tree on average. The average scar area per tree caused by the forwarder was 290 cm^2 (44.9 in^2) while that caused by the harvester was 202.6 cm^2 (31.4 in^2). Greater root damage was observed after forwarder passes.

Table 4 summarizes the results of damage levels and scar measurements in wounded trees caused by the three different logging systems. The average scar sizes observed in skyline units were smaller than those in the tractor and cut-to-length system units. The lowest value of an average scar size was 87 cm^2 (13.5 in^2) at Heavy thinning unit in Walk Thin. The average size of scars in tractor logging units were relatively high, ranging from 242 cm^2 (37.5 in^2) to 356 cm^2 (55.2 in^2).

Scar Height

The skyline logging system left the highest scar on average, followed by cut-to-length and tractor logging systems. Scars from tractor logging were concentrated at heights less than 61 cm (2 feet): 45.5% and 59.7% of scars in tractor logging units were located below 61 cm (2 feet) in Mill Thin and Tap Thin, respectively. The ratios of scars less than 61 cm (2 feet) height to the total were 12.2% in skyline and 29.3% in cut-to-length logging units. In the cut-to-length system, scars caused by the harvester were lower on average than those by the forwarder. Sixty-three percent of the scars caused by the harvester were lower than 1.3 m (4 feet) while 57% of the scars caused by the forwarder were lower than 1.3 m (4 feet).

Scar Locations in Quadrants

Figure 1 illustrates scar locations in relation to each quadrant for the three logging systems. Scars in tractor

Table 3. Comparison of damage characteristics caused by harvester and forwarder.

	# of trees damaged (224 trees total)	# of trees root damaged	Dist. from skid trails m (feet)	# of scars per tree	Scar height m (feet)	Scar width m (inch)	Scar length m (inch)	Scar area per scar cm^2 (in^2)
Harvester only	143 (63.8%)	4	5 (15.2)	1.4	1.6 (4.9)	1 (3.3)	2 (6.4)	144 (22.3)
Forwarder only	64 (28.6%)	6	4.2 (12.9)	1.9	1.9 (5.9)	1.2 (3.7)	2.4 (7.3)	179 (27.7)
Both	17 (7.6%)							

Table 4. Descriptive statistics of residual stand damage after commercial thinning in the Willamette National Forest.

Sale (Logging System)	Thinning Treatment	Damage Level (%)	DBH of Damaged trees cm (in)	# of scars (/tree)	Average Scar Height cm (in)	Average Scar Width cm (in)	Average Scar Length cm (in)	Average Scar Area cm^2/scar (in^2/scar)	Average Scar Area cm^2/ha (ft^2/ac)
Walk Thin (Skyline)	Heavy	18.8	34.8 (13.7)	2.3	17.3 (6.8)	8.9 (3.5)	12.4 (4.9)	87.1 (13.5)	2,755 (1.2)
	Light	13.5	31.8 (12.5)	1.8	21.3 (8.4)	7.1 (2.8)	18 (7.1)	153.1 (23.6)	5,510 (2.4)
	Light w/ Patches	20.2	30.7 (12.1)	2.4	21.1 (8.3)	10.4 (4.1)	26.2 (10.3)	265.8 (41.2)	11,020 (4.8)
Mill Thin (Tractor)	Heavy	25.4	35.3 (13.9)	2	8.9 (3.5)	12.7 (5)	21.1 (8.3)	241.9 (37.5)	11,020 (4.8)
	Light	18.4	32 (12.6)	1.2	8.6 (3.4)	13.7 (5.4)	22.3 (8.8)	337.4 (52.3)	7,806 (3.4)
	Light w/ Patches	9.2	34.3 (13.5)	1.2	4.8 (1.9)	11.7 (4.6)	30.5 (12)	356.2 (55.2)	4,362 (1.9)
Tap Thin (Tractor)	Heavy	7.5	36.8 (14.5)	1.1	4.6 (1.8)	11.2 (4.4)	20.3 (8)	322.6 (50)	2,296 (1)
	Light	20.2	34.5 (13.6)	1.7	13.5 (5.3)	14.7 (5.8)	20.1 (7.9)	314.9 (48.8)	15,152 (6.6)
Flatthin (Cut-to-length)	Heavy	34.2	39.4 (15.5)	2.2	17 (6.7)	9.9 (3.9)	17.8 (7)	180.6 (28)	24,335 (10.6)
	Light	41.3	37.8 (14.9)	1.7	14.5 (5.7)	9.4 (3.7)	14.2 (5.6)	113.5 (17.6)	11,249 (4.9)
	Light w/ Patches	31.9	36.8 (14.5)	1.2	7.6 (3)	15.5 (6.1)	32.5 (12.8)	387.1 (60)	25,483 (11.1)

logging units were highly concentrated on quadrant #2 facing toward the skid trails (53.4% in Mill Thin and 61.3% in Tap Thin). Skyline and cut-to-length thinning almost evenly had scars on every quadrant with the lowest portion (14.6% and 8.3%) in quadrant #1 and #4, respectively. In the cut-to-length system, the harvester evenly created scars on quadrant #1, #2, and #3 with the lowest in quadrant #4, while 45% of the scars caused by the forwarder were located on quadrant #2.

Gouge Damage

The highest gouge damage was caused by tractor logging (31.8%), followed by cut-to-length (26.3%) and skyline logging (16.8%) (Table 5). In tractor and cut-to-length logging units, more than 10% of the scars had gouge damage covering 25% or more of scar area, while only 4.2 % of scars in skyline logging units had this damage. The severe gouge damage occurred on trees along the skid trails or skyline corridors. For the depth of gouge damage, 16.8% of skyline logging scars had gouge damage more than 1 cm in depth. It was 31.8% and 26.3% in tractor and cut-to-length logging scars, respectively (Table 6).

Damaged Tree Distances from the Skyline Corridors/Skid Trails

Most of the damage (73.8% in Mill Thin and 73.1% in Tap Thin) occurred on the trees that were within 4.57

m (15 feet) of a skyline corridor or a trail centerline without any trend among thinning treatments. These damages were especially concentrated on the trees along the corridors/trails within 3 m (10 feet), accounting for 57.5% and 59.6% of the total damage for Mill Thin and Tap Thin. Skyline and cut-to-length thinning had 54% and 59.6% of damage to crop trees within 4.57 m (15 feet) of a skyline corridor or a trail centerline, respectively. The average distances of total damaged trees for three logging systems are shown in Figure 2. In the cut-to-length systems, the harvester and forwarder caused almost the same proportion (67.2% and 66.1%) of damage within 15 feet from the centerline of skid trails.

DISCUSSION

Many compounding variables affect stand damage in thinnings. One of these variables, width of skid trails, heavily affected wounding in tractor logging units. Several papers reported that damage occurrence was higher with tractor thinning than skyline thinning (Aulerich *et al.* 1976, Carvell 1984, Fairweather 1991). However, two tractor logging units, Heavy thinning in Tap Thin and Light with patches in Mill Thin sustained only 7.5% and 9.2% of damage levels, respectively. Old skid trails, which were 6 - 7.2 m (18 - 22 feet) wide, were used for skidding in these two units. We rarely saw wounding on trees along the skid trail in these units, while wounding was heavily concentrated on trees near the trails in other units. The width of skid trails in other tractor units was 4.6 m (14 feet) or narrower. Different intensities of thinning treatments could be another factor affecting damage level; however, there was no trend of wounding crop trees in relation to different thinning treatments in our study.

Damage levels reported are heavily affected by the minimum size of scar which constitutes damage. The minimum scar size varies among agencies and is often ambiguous. The damage level of Light thinning unit in the Flatthin sale drops from 41.3% to 4.7% if only scar sizes greater than 465 cm^2 (72 in^2) are considered a damaged tree. Most scars (69%) caused by the cut-to-length system were smaller than 232 cm^2 (36 in^2), while there were 45% in Tap Thin and 54% in Mill Thin, where a tractor system was used. In contrast, the damage level of Light with patches unit in Mill Thin sale only drops from 9.2% to 4.6% with scars larger than 465 cm^2 (72 in^2). This also indicates that tractor logging causes more severe scarring (bigger scars) to crop trees than cut-to-length logging.

The question of damage level also should be related to the impact of future stand development and expected

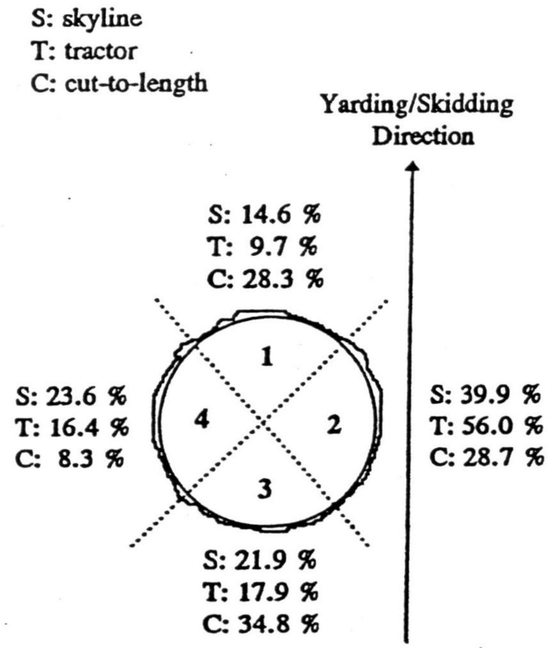

Figure 1. Scar locations created by three logging systems.

Table 5. Gouge areas.

Gouge areas [a](%)	Skyline [b](%)	Tractor [b](%)	Cut-to-length [b](%)	Helicopter [b](%)
0	83.2	68.2	73.7	0
1 - 25	12.6	19.9	15.7	0
25 - 50	4.2	7.3	5.5	0
> 50	0	4.6	5.1	0

Table 6. Gouge depths.

Gouge depth (cm)	Skyline [b](%)	Tractor [b](%)	Cut-to-length [b](%)	Helicopter [b](%)
0	83.2	68.2	73.7	0
> 1	15.3	28.4	22.6	0
1 - 2	1	2.7	3.3	0
> 2	0.5	0.7	0.4	0

[a] Values represent % of scar area occupied by gouge area.
[b] Values are ratios from total # of scars.

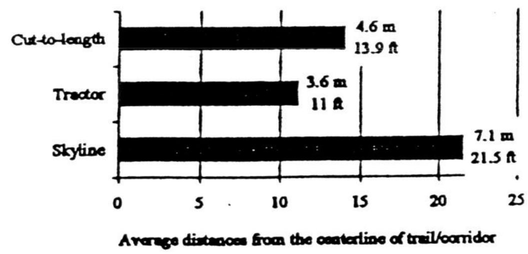

Figure 2. Location of damaged trees.

outcomes in timber volume and quality. Different logging systems cause different types of residual stand damage. For example, tractor logging often caused scarring at the butt log, where tree value is concentrated. These wounds tend to develop severe decay over time. In contrast, skyline and helicopter thinning does not cause any root damage. The scars caused by helicopter and skyline logging have very limited to no gouge damage. Eighty-four percent and 100% of scars had no gouge damage in Walk Thin (skyline) and our Hebo study unit (helicopter) (Pilkerton *et al.* 1996). Although the damage level (11.1%) at Hebo was higher than that (7.5%) in a tractor logging unit at Tap Thin, the residual trees at Hebo may be less affected by logging damages in their future growth and values than the trees in the tractor unit. In practice, the inspector determines the level of damage based on current and potential values of trees in the future in relation to species, size, age and growth rate.

In our studies, loggers often used "tree pads" to protect leave trees at the landing and along skyline corridors and skid trails. They used two types of tree pads, plastic and rubber, and preferred to use rubber because it stayed on the tree better. The rubber pad was heavier than the plastic. The results of scar height and locations should help people understand where and how high tree pads are needed. The results of scar locations in each quadrant also indicates the location that should be covered for each logging system.

A harvester operator should put more effort into minimizing stand damage than may be needed from a forwarder operator since the harvester causes more wounding (about 70%) than the forwarder (30%). However, wounding by the forwarder is usually deeper and larger than the harvester, especially leaving more root damage by its repeated traffic. The efforts by the two operators should be supported at the planning stage, such as optimal spacing of trails for the harvester and straight trails as much as possible for the forwarder.

Harvesting Variables affecting Damage Level

Based on our study results and observations during the thinning operations, the following harvesting variables affect residual stand damage:

(1) **Width of skid trail**: Trees near the trail are often scarred by logs and tire or tracks of skidders and forwarders. Root systems are also severed or scarred if a tree is located by the trail. When winching logs from a narrow trail, the skidder often hits trees when repositioning to avoid hang-ups due to a stump or other trees. Scarring or any root damage near the skid trail is usually large and severe because damage is created by a big or multiple impact from logs and equipment. Increased damage was noticed along the skyline roads where the skyline is not located in the middle of corridors.

(2) **Tree size**: When a large tree is falling, heavy bole or broken large branches scratch the bark and remove the branches of residual trees. Sometimes, tops of small trees are broken when felling large trees. With a single grip harvester, a large tree often requires the machine to be off the trails due to handling limitations with large diameter trees, resulting in a greater chance of creating damage to crop trees by the machine body and felling head.

(3) **Landing**: For ground-based systems, a large central landing which has a decking place tends to leave less logging damage to remaining trees. In continuous landings where landing areas are usually small and decking places are not available, severe scarring by sorting and loading activities frequently occurred. Also, since there is no decking place available, the sorted logs are leaned and rubbed against crop trees, scarring them. Landing locations and skid trail layouts must also consider soil disturbance and skidding production.

(4) **Condition of skid trail**: A trail which has old or new high stumps forces the skidder to one side of the trail, increasing the chance of impacting trees near the trail. Trees along a corner or sharp curve of the trail have high probability of being damaged by tires and logs. Root systems are often severed by skidder blading to level the trail surface. Cutting low stump heights in skid trails is important.

(5) **Skyline height**: Tree crown or tops can be removed by a high skyline which runs through or above the crown of crop trees. During lateral yarding, the lateral excursion of a skyline creates damage to the crown or the bole of remaining trees, depending on the skyline height. The use of intermediate supports or leaving rub trees reduces skyline lateral excursion.

(6) **Skid trail/skyline road spacing**: Wider spacing of trail/road requires increased winching or lateral yarding distance. This causes a higher chance of rubbing by a cable or of impact by logs being skidded. In thinning operations, loggers target an average spacing to 40 m (120 feet) for tractor and 50 m (150 feet) for skyline logging. If the spacing is greater than 16.5 m (50 feet) in the cut-to-length system, harvesters need to be off the trail to cut the trees due to their limited reach.

(7) **Felling pattern:** Directional felling or a herring-bone felling pattern helps to reduce damage by reducing log swing during lateral inhaul or winching logs. In the cut-to-length thinning, the forwarder can control logs better when logs are bunched perpendicular to the hauling direction and are well sorted by the harvester according to diameter classes, and saw and chip logs.

(8) **Species:** We often noticed the rubbing trace on the bark of standing trees, which occurred during felling, skidding or winching. Because of its thick bark, Douglas fir tends to be less susceptible to scarring than western hemlock or other thin bark species.

(9) **Sale administrators:** The study areas were managed by the Forest Service. During the thinning operations, sale administrators kept reminding loggers to minimize the damage by saying that excess damage would not be tolerated. The penalty for excess damage includes the shut down of logging operations until sapflow stops completely. Sale administrators also have authority to permit cutting of trees that were originally designated crop trees, if trees are seriously damaged.

(10) **Planning and layout**: Planning is the most essential function to be performed in a thinning operation. It is essential because it provides the discipline that welds together all parts of the harvesting system, identifying and resolving conflicts, recognizing constraints, and providing for an orderly input of resources. During the planning process, all identified or possible problems can be removed.

(11) **Logger's effort and experience**: No matter how well planned and designed the thinning operation, loggers need to make an effort to minimize logging damage. Loggers' skill and experience supports their efforts to avoid stand damage.

SUMMARY

The most typical type of damage to crop trees in every logging system unit was scarring, accounting for more than 90% of the total damage. Crown damage and broken-tops were often observed in the skyline system, while root damage was prevalent in tractor and cut-to-length logging units. The highest incidence of damage, 41.3% to remaining trees, occurred at the Light thinning unit thinned by a cut-to-length system. This damage level drops to only 2.3% if only scar sizes greater than 929 cm^2 (144 in^2) were considered as a damaged tree. With the same consideration, damage levels significantly drop to 1.5%, 1.6%, and 5.5% in skyline units but are relatively high in tractor logging units. In the cut-to-length system, the harvester damaged 63.8% of residual trees, more than twice the damage created by the forwarder (28.6%). Only 7.6% of damaged trees were impacted by both the harvester and the forwarder. Attention to a number of important harvesting variables can affect stand damage level in thinning for skyline, tractor and cut-to-length logging systems.

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