Impacts on soils and residual trees from cut-to-length thinning operations in California's redwood forests

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Abstract

Cut-to-length (CTL) harvest systems have recently been introduced for thinning third-growth, young (<25 years old) redwood forests (*Sequoia sempervirens* (Lamb. ex D. Don) Endl.) in northern California. This type of harvesting can effective for thinning overstocked stands consisting of small-diameter trees. However, forestland managers and government agencies overseeing forest operations have concerns about potential environmental impacts such as soil compaction or damage to remaining trees because harvesting often occurs when the soil is wet. This study was designed to (1) determine changes in soil physical properties (2) measure residual stand damage from a CTL thinning operation. Soil samples were collected from transects at two locations (track and center) on forwarder trails and reference (un-trafficked) points at three levels of soil depths (0-5, 10-15, and 20-25 cm). Stand damage was assessed as tree scaring was measured on all tree-sizes. We found significant differences between the wheel track and reference at the soil surface. There was no significant difference in the water infiltration rate between three locations because of high soil variability within small number of sample sizes, high moisture content, or high soil porosities. The way in which the scars occur depends on the composition of the redwoods. We measured larger sized-scars on remaining trees where trees were left in clumps as compared to individual trees, but the magnitude of damage was not different. Due to the few measureable effects on soil physical properties and residual tree damage, CTL thinning is viable during winter in this area.

Keywords: mechanized system, soil compaction, slash, stand damage, infiltration rate, scar,

Introduction

Thinning activities in redwood forests (*Sequoia sempervirens* (Lamb. ex D. Don) Endl.) can improve wildlife habitat, forest health, and yield intermediate revenues for landowners. Thinning redwood stands will also help produce beautiful wood products for an additional source of revenue (Thornburgh et al. 2000). In this regard, thinning can be a significant method for managing redwood forests. In addition, thinning methods are being used increasingly. However, during mechanized harvesting, environmental impacts may be considerable. For example, soil compaction or tree damage can have large impacts on the growth and health of the remaining

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stand. Soil compaction is defined as a process that occurs when the pressure from wheel traffic pushes aggregates together (Wolkowski and Lowery. 2008). It can reduce air-filled porosities, (Froehlich et al. 1980), limit root access, and disrupt the respiration, which has a negative influence on the physiological function of a tree, resulting in reduced growth. There have been many studies examining how soil properties alter the severity of soil compaction. Soil texture (Heilman. 1981; Pierce et al. 1983), moisture content (Coder. 2000; Han et al. 2006; Han et al. 2009), number of machine passes (McDonald and Seixas. 1993; Armlovich. 1995), slash layer (Han et al. 2006; McDonald and Seixas. 1997), and harvesting system (Allen 1997; Lanford and Stokes, 1995, Han et al. 2009) are some of the influences on the degree and extent of compaction. However, soil can be highly variable (McDonald and Seixas. 1997; Han et al. 2006). In addition, the amount of slash remaining on the soil surface is important as soil moisture and the number of machine passes increase (Han et al. 2006).

Scarring from operations often does not affect tree growth (Bettinger and Kellogg. 1993), but tree injury can provide a route for fungi; causing defects such as pitch rings and resulting in a loss of tree volume and negative visual marks (Han. 1997). Even though these damages are related to future stand development, there is no specific definition of stand damage. Han and Kellogg (2000) define scar damage as a removal of the bark and cambial layer, exposing the sapwood. The severity of stand damage depends on several factors such as harvesting systems (Lanford and Stokes. 1995; Han. 1997), and species (Bettinger and Kellogg. 1993). The residual stand damage by forest operation frequently occurs during transport of timber (Han. 1997; Froese and Han. 2006; Kosir. 2008).

For these reasons, it is important for forest managers to select the appropriate harvesting method for their soil and stand condition. A cut-to-length (CTL) system, (ground-based harvesting using a harvester and a forwarder) has been introduced to produce small-diameter timber in third-growth, young redwood forests (Adebayo et al. 2007). The CTL system removes the branches and tops from harvested trees, and uses this to cover the forwarder trails; thereby minimizing equipment pressure on the soil. Bettinger and Kellogg (1993) showed that in the Cascade Range of western Oregon, a cut-to-length system caused damages resulting in minimal future volume loss due to its low percentage of scars. In a mixed conifer stand in northern Idaho, 84 % of damages for all species were considered as small size (192 cm^2).

The purpose of this study was to determine the degree of soil compaction during winter season logging operations in a redwood stand. Specifically, we determined (1) changes in soil physical properties (bulk density and water infiltration) at three locations (track, center, and reference point (un-trafficked)) at three soil depths (2) tree scar characteristics, and distribution, (3) difference in scar characteristics among individual trees and clumps of trees.

Methodology

Site description

The study was conducted in the Crannell tract, a Green Diamond Resource Company forest in northern California on the road CR 1200 (41°00'48.5''N, 124°04'29.6''W). The study area was 10.1 ha including 1.2 ha Watercourse and Lake Protection Zone (WLPZ) at an elevation of 126 m with a flat ground slope (approximately 0 %). Average tree diameter at breast height (dbh) and height were 20 cm and 19 m, respectively (Table 1). There were 2,390 trees per ha, with redwood being the most dominant species (77%), followed by red alder (17%), Douglas-fir (5%), and Sitka spruce (1%). After thinning, redwood was still dominant in the study area with average diameter and height of 23cm, 19 m, respectively. Basal area changed from 98.7 m^2 per ha to 39.7 m^2 per ha and there were 768 trees per ha. Soil class in the study area was Ultisols and particle distribution using hydrometer test showed that silt loam (sand: 37%; silt: 56%; clay: 7%), and 14% of soil top layer was composed of organic matter (Table 2). This was the third harvest operation in the stand, with the last harvest occurring 30 years ago.

Table 1 Stand composition characteristics including average dbh, height, and biomass amount before and after harvesting in study area (10.1 ha).

Characteristics		Pre-thinning	Post-thinning
Average dbh (cm)		20	23
Average height (m)		19	19
Average basal area (m^2/ha)		99	40
Stand density (TPH[a])		2,390	768
Amount of slash on the trails[b] (kg/m^2)		2.3	29.8
Species percentage (%)	redwood	77	79
	red alder	17	15
	Douglas-fir	5	4
	Sitka spruce	1	2

Note: [a] Only included trees 5 cm or greater in diameter at breast height (dbh).
[b] The Brown method (1974) for downed debris and allometric equations (and Kisha and Han. 2015, Jenkins et al. 2003) for additional slash generated from thinning operations. We assumed that 90 % of slash from thinning operation was covered based on visual observation. Actual width of skid trail was about 3.7 m, however, we assumed the width of trail as 4.5 m since the slash was not organized within skid trail exactly. Slash sometimes covered outside of trails. Also, we used the unit as green ton assuming that slash has 50% moisture content and converted to kg.

Table 2. Summary of pre-harvest soil characteristics at each soil depth.

Texture: Silt loam		Class	Soil depth	Organic matter	Moisture content
Particle size	%		cm	%	%
Sand	37	Ultisols	0-5	14	58
Silt	56		10-15	13	52
Clay	7		20-25	12	51

Harvest operations

A commercial thinning operation was performed at the study area. Cut-to-length harvesting occurred between January and March 2017 using a single-grip harvester (Ponsse Bear) with a Ponsse H8 harvester head and a forwarder (Ponsse Buffalo). The typical weight of Ponsse Bear is 24,500 kg, and the forwarder is composed of bogie tracks with eight wheels, having a weight of 19,800 kg. Due to heavy rains during the winter, operations were frequently stopped. The objectives of the thinning prescription were to: (1) cut the dead trees (2) increase spacing (3) reduce forest fire fuel continuity. In addition, the operator did not cut trees greater than 60 cm in diameter at breast height (DBH), maintained at least 60% canopy closure, and retained the most healthy and vigorous dominant and codominant trees at a stocking level of at least 23 m^2 per ha basal area. Moreover, the harvester operator was directed to create a large amount of slash to minimize soil impacts.

After harvesting, all forwarder trail data were collected by walking each trail with a GPS unit (Garmin). The width of each trail was measured every 20 m to determine mean of trail width. The average width and total length of skid trail were used to determine trail coverage. We mapped each trail from the log landing using ArcGIS 10.1 to determine the number of transects needed. Therefore, we could know the relationship between the number of passes and bulk density instead of counting the number of machine passes manually since as the distance from landing site increases, the machine passes decrease (Han et al. 2009). The mean of trail width was 3.7 m and a total 19% of the whole area was disturbed by machine.

Data collection for soil and tree damage

Soil samples were collected with a slide hammer corer (AMS Inc, American Falls, ID; 90.59cm^3). Samples were collected from the 0-5, 10-15, 20-25 cm depths in the mineral soil. Before collecting soil cores, we removed the slash layer and forest floor to locate the top of the mineral soil. Bulk density cores were collected on a 3.6 m transect installed every 150 m perpendicular to a forwarder trail. Soil cores were collected in one of the wheel tracks, centerline, and 1.8 m away from the track (reference point). We assumed that at the reference point, there were no passes from either harvester or forwarder, indicating no soil disturbance. Cores were placed in plastic bags for transporting from the field to laboratory. In the laboratory, soil samples were weighed, dried at 105 ℃ for 24 hours in the oven, and reweighed. A total of 297 samples were collected for bulk density. Moreover, during the harvest operations, we collected additional soil cores to determine soil moisture content during operations.

A mini-disk infiltrometer (Decagon Device, Pullman, WA) with a diameter of 3.1 cm was used to measure water infiltration rate (WIR) with the suction rate adjusted to 2 cm. Water infiltration data were collected along the same transects as BD. The WIR samples were collected adjacent to the BD samples. Infiltration was only collected from the mineral soil surface. We recorded water volume every 30 seconds for a total of 300 seconds. Based on the mini-disk data, we calculated hydraulic conductivity (Zhang. 1997), which requires measuring cumulative infiltration rate versus time and fitting the results with the several functions. A total of 99 samples for WIR were collected.

Similar to Han (1997), we defined stand damage as the removal of the bark and cambial layer, exposing sapwood. We used a systematic sampling method since this method gives similar results to total tree sampling. Each damaged tree had equal probability of selection (Han, 1997). We installed transects every 106 m (ranging from boundary to boundary) perpendicular to the main direction of the skid trails and used fixed-circular plots (0.04 ha) to determine tree damage. Since crown damages do not occur frequently when using ground-based harvest systems, we examined only scar damage on the stem by qualitative standards. We evaluated the number of scars per tree, number of trees damaged per ha, height of damage from ground level, distance from the scar to the centerline of the skid trail, and scar size (width and length). We measured each scar regardless of size. Additionally, we observed scar location as one of the following: #1 facing the skid trail; #2 rotated clockwise from skid trail; #3 opposite to skid trail; #4 rotated counter-clockwise from skid trail.

Slash determination and statistical analyses

The operator was willing to make more slash than other operations to prevent disturbance on the soil. Slash amounts were estimated by downed woody debris survey method using the Brown transect method (1974), and allometric equations (Kisha and Han. 2015; Jenkins et al. 2003) Slash covering the forwarding trail increased approximately 93% (from 2.3 to 29.8 kg/m^2 after harvesting). A total of 32.1 kg/m^2 of slash was on the forwarding trail.

Data analysis was conducted using Statistical Package for the Social Sciences 24 (SPSS, Armonk NY), and R Package (R Development Core Team (2008)). We test for normality using the Shapiro-normality test. The Kruskal-Wallis test was used to compare the level of soil compaction among three sampling locations: track, center, and reference at each depth, and Holm's method was used for post-hoc testing. The Mann Whitney U-test was used to determine the scar size differences among clumped and non-clumped trees.

Results

Soil physical properties

At the reference point, the average BD values were 0.69 g/cm^3 at the 0-5 cm depth, 0.98 g/cm^3 at the 10-15 cm depth, 0.97 g/cm^3 at 20-25 cm depth (Table 4). At the 0-5 and 10-15 cm, there was a significant difference between track and reference ($p < 0.05$), however, there was no difference between track and center ($p > 0.05$). However, there was no noticeable difference between the three locations at 20-25 cm. The largest BD increase was in the surface 0-5 cm (approximately 25%) and decreased slightly with soil depth. On a reference point, average water infiltration rate (WIR) was 1.25 cm/hr. At three points, even though WIR on reference was slightly higher than that on track, there was no significant difference between three locations Also, there was no significant relationship between distance from landing and BD at 0-5 cm ($p>$ 0.05).

Table 4. Soil bulk density (g/cm^3) and infiltration rate (cm/hr) measurement at different locations (track, center, reference) along the forwarding trails (n = 33).

Measurements	Soil depth (cm)	Reference	Center	Track	p-value*
Bulk density (BD)	0-5	$0.69±0.17^a$	$0.80±0.18^b$	$0.83±0.24^b$	0.0063
	10-15	$0.98±0.10^a$	$1.03±0.14^{ab}$	$1.08±0.13^b$	0.0330
	20-25	$0.97±0.23^a$	$1.09±0.17^a$	$1.13±0.14^a$	0.6664
Water infiltration rate (WIR)	0-5	$1.25±1.48^a$	$1.87±2.78^a$	$1.17±1.43^a$	0.6579

Note: * Kruskal-Wallis test, $p < 0.05$. The same letters in the each depth indicates that bulk densities between sampling locations are not significantly different (p >0.05).

Stand Damage

Table 5 summarizes the result of the scar damage from harvest operation. A total of 16.2% trees were damaged, had an averaged dbh of 24.8 cm, and averaged 1.7 scars per trees. Average scar width and length was 9.0, 27.3 cm, respectively, and average distance from centerline was 4.8 m with an average height from the ground of 1.3 m. (Table 6). There was a little correlation between the number of scars on a tree and dbh ($p > 0.05$). During operation, over 62% of tree damage was less than 1.5 m from ground, and 72% occurred within 4 m from centerline of track (Table 7). Also, a scar width less than 10 cm was composed of 65%, and 82% of scar length was less than 40 cm.

Based on Table 8, the majority of scars occurred at #1, and, there were the least scars on #3. While trees in clumps followed this tendency, there was no significant difference among the location by quadrant in individual tree. When compared scar size according to tree composition in which there was a slight difference of scar width between clump and individual tree (Table 9), however, they were not statistically different ($p > 0.05$). However there was a significant difference of scar length between clump and individual trees ($p < 0.05$).

Table 5. Summary of residual stand damage resulting from a cut-to-length thinning operation.

Percentage of damaged tree[a] (%)	Number of damaged trees[b]				dbh of damaged trees (cm)	# of damaged trees per ha	# of scars per tree
	Total	RW	DF	AR			
16.2	96	81	5	10	24.8	107.7	1.7

Note: [a] Calculated based on all scar sizes. Value represents the ratio from total number of trees we sampled.
[b] RW: redwood, DF: Douglas-fir, AR: red alder.

Table 6. Summary of scar characteristics from thinning operation, and correlation between dbh and number of scars.

Average				Correlation between dbh and # of scars	
Scar size		Dist from centerline (m)	Height from ground (m)		
Width (cm)	Length (cm)			*r**	*p*-value
9.0	27.3	4.8	1.3	-0.1963	0.0552

Note: ******r* is a correlation coefficient.

Table 7. Scar distribution according to distance from centerline, height from ground, and scar size (width and length).

Dist from centerline (m)	Percentage (%)	Height from ground (m)	Percentage (%)	Width (cm)	Percentage (%)	Length (cm)	Percentage (%)
0-2	61	0-1	35	0-5	27	0-20	45
2-4	11	1-1.5	27	5-10	38	20-40	37
4-6	20	1.5-2	22	10-15	19	40-60	10
6-8	2	2-2.5	11	15-20	11	60-80	4
> 8	6	> 2.5	5	> 20	5	> 80	4
Total	100	Total	100	Total	100	Total	100

Table 8. Scar distribution by quadrants according to tree composition.

Scar location	# of scars composition		# of scars	
	Clump	Individual	Total	Percentage (%)
# 1	43	15	58	36
# 2	30	14	44	27
# 3	8	17	25	16
# 4	22	12	34	21
Total	103	58	161	100

Table 9. Mean difference of scar size in individual and clump tree.

Width (cm)					Length (cm)				
Individual		Clump		*p*-value*	Individual		Clump		*p*-value*
n	cm	*n*	cm	0.1611	*n*	cm	*n*	cm	0.0001
58	8.1	103	9.1		58	16.7	103	28.1	

Note: *Mann Whitney U-test, $p < 0.05$

Discussion

Soil compaction

The BD results provide data similar to several previous studies (Han et al. 2009; Han et al. 2006; McDonald and Seixas. 1997). Han et al (2009) indicated that CTL system produced no significant differences from the center of the track and the reference on ashy loamy soils in northern Idaho at soil surface. Our data indicate that there was a difference between center and reference at the soil surface (0-5 cm) We noted that when the harvester and forwarder moved back and forth, they occasionally drove through the centerline of the skid trail which likely produced these changes. In addition, the BD in the track had a significant difference compared to reference point. As expected, BD decreased steadily as soil depth increased (Han et al. 2009). McDonald and Seixas (1997) also found the similar result that at the soil surface (0-5 cm) BD was significantly greater regardless of slash amount, however, at 15 to 20 cm there was no significant BD increase. The ideal BD for a silt loam soil is less than 1.30 g/cm^3, and root growth can be impaired over 1.60 g/cm^3 (Pierce et al.1983). In addition, Daddow and Warrington note that silt loam soils (without rocks) reach a root limiting BD at 1.4 g/cm^3. Both of these values were not exceed in our study and we expect that root growth was likely unaffected. However, site-specific measurements on the relationship of BD and root growth should be considered (Miller et al. 2004).

BD in the wheel tracks were significantly different compared to those on the reference, however, the values on the track were lower than other studies; even in wet weather. Soil moisture content and texture are critical factors for determining the extent and duration of increased BD during harvesting. The soil condition in our study, silt loam with high moisture content, is easily affected by machine pressure. However, we requested that all the slash generated during harvesting be placed on the skid trails to minimize soil compaction. This was also successful in limiting ruts and soil displacement although we did not specifically measure these. Using slash to limit soil disturbance is critical for maintaining soil quality (McDonald and Seixas, 1997, Han et al. 2006). Large amount of slash (40 kg/m^2) on the soil surface, even when the soil is wet provided an affective cushion from machine trafficking (Han et al. 2006). However, it indicated that just slash was not effective to reduce soil strength. Heavy slash with wet condition could provide an effective cushion from machine pressure compared to dry condition. In bulk density, a greater slash amount appeared effective on the wetter soil rather than drier soil (McDonalad and Seixas. 1997).

In addition, bogie-track was used to harvester and forwarder, which can be effective for minimizing ground pressure on soil compared to using conventional wheel (Gerasimov and Katarov, 2010, Bygdén et al. 2003). In a previous study at sand, fine sand, and silt soil types, bogie-tracks had less rutting damage and a lower soil resistance as compared to wheel tracks (Bygdén et al. 2003). Moreover, the bulk density of the reference point was originally low than other studies, indicating greater amount of soil porosities. Soil porosity was estimated from the BD data (Table 10). At the 0-5, and 10-15 cm depth, soil porosities in the wheel track is much lower than those at the reference point. Coder (2000) indicates that an ideal soil has 50% pore space. This is lower than that what we calculated for the wheel tracks, since our initial porosities were quite high, this might be expected. Also, initial bulk density and number of machine passes can determine the subsequent soil recovery (Page-Dumroese et al. 2006). So this site may recover to pre-harvested conditions faster due to its low initial bulk density and few numbers of passes. However, fine-textured soils recover more slowly if there isn't a freeze-thaw cycle or less compacted (Page-Dumroese et al. 2006).

Table 10. Soil porosity (%) calculated from bulk density (g/cm^3) at different locations (track, center, reference) along the forwarding trails (n = 33). The particle density was assumed to be 2.65 g/cm^3.

Measurements	Soil depth (cm)	Reference	Center	Track	p-value[*]

	0-5	74±6.7[a]	70±6.8[b]	69±9.1[b]	0.0063
Soil porosity (%)	10-15	63±6.4[a]	61±5.6[ab]	59±5.1[b]	0.0330
	20-25	59±6.7[a]	58±7.1[a]	57±5.7[a]	0.6664

Note: * Kruskal-Wallis test, $p < 0.05$. The same letters in the each depth indicates that bulk densities between sampling locations are not significantly different ($p > 0.05$).

We ran a Pearson's correlation test to see the relationship between distance from landing place and bulk density at 0 to 5 cm. Unlike other studies (Han et al. 2009; McDonald and Seixas. 1997), we found no relationship between distance from landing and bulk density ($r = 0.0002$, $p > 0.05$). Han et al (1997) evaluated the impact of a cut-to-length operation on BD using regression models that have a negative coefficient of distance from landing place and were run at 25 to 30% moisture content. The skid trails in our study were too short to detect the BD difference along the trail length. Our trails were less than a half the length as compared to Han (1997) study, and we would say that we had fewer machine passes. Han et al (2006) also found that the number of machine passes was strongly related slash amount and moisture content in BD changes. The large amount of slash on our trails (32.1kg/m^2) buffered the soil, even soil moisture content was high.

The WIR results did not follow changes in BD. WIR was slightly lower on the track than reference point, but there was no significant difference between two locations. Another study showed that an increase in bulk density is not always associated with a significant decrease in infiltration (Aust et al. 1992), which was similar to the results of our study. The lack of significant differences in WIR could be related to high spatial variability in infiltration rather than bulk density and its insufficient sample sizes (Huang et al. 1996). Soil porosity in the wheel track was significantly different than the reference, however, it is still relatively high.

Due to its flat ground slope, the high levels of soil organic matter could reduce soil erosion even with its high moisture content. On other sites, the lack of forest residue and bare soil exposed to high intensity rainfalls are factors of soil erosion (Franzluebbers. 2001). There was a lot of slash between the tracks compared to the wheel tracks so we would say there was not serious soil erosion.

Stand damage

Only 16.2% of trees were damaged in our site during CTL harvesting. Even though sapwood is not decay-resistant, redwood, like other members of the family Cupressaceae, has decay-resistant bark and heartwood, and is virtually immune to insects and diseases (Krokene, Nagv and Krekling. 2008). Also, the bark of trees in this family is very interesting structurally, consisting of layers of fibers sandwiching cells filled with toxins called polyphenolic parenchyma in addition to sieve cells (Krokene, Nagv and Krekling. 2008). For these redwood characteristics, it can prevent generating deep scars.

Our data support the work of others who have examined residual tree scars associated with logging operations (Froese and Han. 2006; Han and Kellogg. 2000). Froese and Han (2006) found that scar height was influenced by distance from the forwarder trail. Likewise, more than half of the damages were generated within 2 m from the forwarder trail indicating that equipment staying on the trail. In addition, Han and Kellogg (2000) found that the average height for scars during CTL operations was 1.4 m, which was similar to our study. Moreover scar location by quadrant was different depending on tree composition. In clump, there was a difference among locations: #1 was highest, and #2 and #4 were similar and #3 was lowest. During harvesting, the logging operator spent a long time grappling a tree in a clump because there was limited space to maneuver the trees. Hence, scar damage to the other trees in the clump would appear #4 and #2. In addition, when a tree from the clump was falling to the ground, it frequently hit both sides of remaining trees.

In individual tree, there was no difference between locations by quadrants, meaning that it could be damaged by falling tree or movement of the harvester and forwarder. Tree damages could be generated when a forwarder moved the logs from deck to bunk. We also noticed that residual unstable trees were felled during wind events, which may have generated additional scars on other trees.

Although there was no significant difference, scar size in the clumps was bigger than that in individual trees. However, we detected a difference in scar length between clump and individual tree ($p < 0.05$). When a harvester grabbed a clumped tree at the first time, they held a slightly higher part than individual tree because it is hard for operators to catch the bottom part. This caused the harvester-head to go down, and a long damage occurred in the process. Fungal decay is highly correlated with scars on residual trees and is better correlated with scar width rather than length (Wallis and Morrison. 1975). We conclude that scar severity was not different. Depending on the size of the scar counted, the percentage of damaged trees also changes. We counted all damage and found that, if scars wider than 5 cm were counted then there was 13.9% stand damage. If we only counted scars greater than 20 cm, then stand damage would have only been 1.7%. This information is critical when determining the acceptable levels of residual stand damage and the risk for disease or insect outbreak.

Conclusion

There are many concerns about logging when soil moisture content is high. We found that with a sufficient level of logging slash applied to the skid trail areas that soil compaction in minimized. There was a significant BD difference between the track and reference at 0-5 and 10-15 cm, however, the initial and final BD values were lower than other studies so that the effect of soil compaction may not be severe enough to hamper root growth. There is no significant difference in infiltration rate between track and reference, which was likely due to high variability of WIR values. Additional sampling would help detect if the significant differences in infiltration rate exist or if similar soils under drier conditions would be affected.

We found little damage to the residual trees with more than of the scars occurring near the skid trail and the ground. This indicates that other studies should evaluate root damages, fungal infestations, and changes in root growth associated with CTL harvesting. The main reasons for scars appears to be from residual trees hitting the remaining trees during a windstorm, the struggle of grappling a tree in clumps, and movement by machines. Therefore, tree damage can be reduced by leaving a remaining low stumps when harvesting or attempting to move machine as far from trees as possible.

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