IMPACTS ON SOILS AND RESIDUAL TREES FROM CUT-TO-LENGTH THINNING OPERATIONS IN CALIFORNIA'S REDWOOD FORESTS

By

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ABSTRACT

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In northern California, a cut-to-length (CTL) system was used for the first time to harvest young redwood forests (*Sequoia sempervirens* (Lamb. ex D. Don) Endl.). However, landowners and public agencies are concerned about the potential negative impacts of CTL logging to soils and residual trees since the extent and amount of CTL impacts are unknown in these forests. This study was designed to (1) determine soil physical property using bulk density (BD) and hydraulic conductivity (HC) (2) examine the characteristics of stand damage after CTL harvesting, and (3) compare the scar size differences between tree growing patterns (individuals vs. clumps). Soil samples were collected from transects at two locations (track and center) on forwarder trails and reference points at three levels of soil depths (0-5, 10-15, and 20-25 cm), and HC data on the soil surface were measured adjacent to the BD sample point. Stand damage was assessed regardless of scar size. I found 25 to 30% increase in BD at 0-5 cm of soil depth on the track compared to reference, but HC showed the inconsistent results due to high variability, so a greater size of HC samples would be needed. Approximately, 16.2-32.2% of residual trees were damaged during operations, and I detected that most damage was located near the forwarding trails and ground level. In addition, I found the larger-sized-

scars on clumped trees compared to individual trees in scar width and length. CTL thinning operations may be viable, however, future studies should be performed after few years to evaluate the feasibility of this harvesting system on longer-term tree growth.

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INTRODUCTION

1.1- Thinning activities in redwood forests

Redwood (*Sequoia sempervirens* (Lamb. ex D. Don) Endl.) is a coniferous species which grows from central California to southwest Oregon. Wood from thinning these stands can provide beautiful products and a source of revenue (Noss 1999). Redwood is one of the most productive timber species in North America because it grows on productive soils, has a long growing season, and a fast growth rate (Oliver et al. 1994). Stand thinning provides one method of providing stocking control to maximize stand productivity. Thinning in redwood stands can result in increased diameter and height growth because of less competition from surrounding vegetation (Cole 1983). In addition, thinning activities can reduce fire hazard, increase residual stand growth (O’Hara et al. 2015), change wildlife habitat, increase forest health (Franklin and Johnson 2012), and yield intermediate revenues (Tappeiner et al 1982).

1.2- Why has mechanized system increased in redwood forests?

In many areas, mechanized harvest systems used for forest thinning operations have increased in popularity because they are effective tools to manage overstocked stands. However, the range of stem sizes, particularly large diameter trees makes thinning in redwood stands difficult with mechanized systems. Thus, in the past, logging operators harvested redwoods using labor-intensive manual felling. Over time, coastal redwood forest composition changed from old growth to young trees (< 25 years old) with a high density, making them accessible to newer mechanized methods. A cut-to-length (CTL) system, which is comprised of a harvester and forwarder, has been recently introduced in northern California. It is optimal for cutting small to medium-sized trees (from 10 to 41 cm DBH), but may have a high initial cost during operations (Kellogg et al. 1992; Bettinger and Kellogg 1993). As the harvester processes the trees, slash (tops and limbs) is placed front of the harvester, and the forwarder uses the same trails created by the harvester.

1.3- Potential environmental impacts from mechanized harvesting

Soil compaction

As using mechanized systems for harvesting increases, potential impacts to environment increase as well. However, the environmental impacts (i.e. soil compaction and residual stand damage) from mechanized logging systems have not been demonstrated in this region before. Soil compaction occurs when the pressure from machine traffics pushes soil aggregates together (Wolkowski and Lowery 2008). Once soil compaction occurred, it can affect to both soil function and tree growth. Compaction can increase soil strength (Froehlich and McNabb 1984) and reduce air-filled porosity, which causes poor root growth and reduced above-ground growth in seedlings (Froehlich et al. 1980). In addition, soil compaction can reduce the infiltration capacity. Decreased infiltration can cause runoff and erosion, resulting in reduced topsoil and water available for tree growth and limit nutrient availability and cycling by soil organisms (Lowery et al. 1996).

The extent, amount, duration, and degree of soil impacts from harvesting depends on several factors such as soil texture (Heilman 1981; Pierce et al. 1983), moisture content (Coder 2000; Han et al. 2006; Han et al. 2009), machine passes (Armlovich 1995; McDonald and Seixas 1997), harvesting system (Lanford and Stokes 1995; Allen 1998; Han et al. 2009), and the amount of woody residue left on the soil surface (McDonald and Seixas 1997; Han et al. 2006). Generally, coarse-textured soils (e.g. sandy or skeletal) are highly-resistant to compaction compared to fine-textured (e.g. silt and clay) soils (Williamson and Neilsen 2000). Also, when soil moisture is high, soils are more prone to the compaction forces of heavy equipment (Adams and Froehlich 1981). CTL harvest systems have become more wide-spread in their use and the system is composed of a harvester and forwarder. As the harvester processes the trees, slash (branches and limbs) is placed in front of the harvester. The harvester and forwarder use the same trails, and the slash mat can significantly reduce rutting and soil compaction (McNeel and Ballard 1992; Han et al. 2009). Han et al. (2006) reported that soil moisture was a major factor affecting the degree of soil compaction when using CTL harvesting at different moisture content levels and there are models which can predict the amount of soil compaction associated with CTL and whole-tree (WT) harvesting systems (Han et al. 2009). These models indicate that the number of machine passes is positively correlated with soil compaction, but most soil compaction occurs within the first five passes. McDonald and Seixas (1997) noted that there was an interaction between the amount of residual woody material left after harvesting and soil moisture when determining the severity of soil compaction during harvesting. They noted that 20 kg/m^2 of slash on moist or wet soil limited the severity of soil compaction, but this was not the same for dry soils.

The type of harvest system can also affect the amount of compaction. For example, Han et al. (2009) compared two ground-based systems (WT and CTL) in the Inland Northwest and concluded that CTL generated less soil compaction (27-28%) than WT system (34-39%) at the 7.5 cm soil depth on volcanic ash-cap, silt loam soil. This was because CTL harvest systems generally use less land area than the WT system. This result is especially critical because most compaction usually occurs during skidding or forwarding operations. For example, a greater land area was impacted when using a skidder as compared to a forwarder system (Lanford and Stokes 1995).

Residual stand damage

Mirkala (2017) indicated that one of the important potential problems from thinning operations is residual stand damage, which may impact tree growth and future timber values. Previous studies reported that scarring from harvest operations did not affect tree growth directly (Bettinger and Kellogg 1993), but provided a pathway for fungi to cause defects such as pitch rings and catfaces at the base of wounded trees, resulting in a loss of tree volume and value (Han 1997). Kiser (2017) reported the growth responses of coastal Douglas-fir (*Pseudotsuga menziesii* (Mirb). Franco) from mechanical damage showed no significant effect between damaged and not-damaged trees but found a difference in crown length.

However, it is difficult for landowners to agree on an absolute definition of what size scar may impede growth or how severe the scar may be (Han 1997). For example, the minimum acceptable scar size can vary from 6.5 cm^2 to 464 cm^2 (Han 1997), and the severity of the tree damage usually depends on the scar location (e.g., roots, stem, or crown) (Han 1997; Tavankar et al. 2015). Han and Kellogg (2000) defined a scar as the removal of wood fibers from the tree stem and recorded scar location (height from ground level) and size (width, height, and depth).

The severity of stand damage depends on several factors such as harvest system (Lanford and Stokes 1995; Han 1997), operator proficiency (Kelley 1983), harvest season (Cline et al. 1991; Limbeck-Lilienau 2003) and tree species (Bettinger and Kellogg 1993). In a loblolly pine (*Pinus taeda* L.) stand using whole-tree (WT) and CTL harvest systems, Lanford and Stokes (1995) reported that WT harvesting had 40% more scars that were 10 times larger than CTL harvest systems. Furthermore, Limbeck-Lilienau (2003) suggests that in mountainous terrain 43% of the residual trees were damaged during WT harvesting while only 20% of the trees were damaged in the CTL units. Residual stand damage frequently occurs during timber transport (i.e. skidding and forwarding) (Kelley 1983; Han 1997; Košir 2008). Froese and Han (2006) found that when using a CTL system, damaged trees were located near forwarding trails, not randomly throughout the stand. In addition, the timing of harvest operations can help minimize stand damage. For example, winter operations in Austria caused less damage than summer logging (Limbeck-Lilienau 2003). Cline et al. (1991) reported the greatest differences in damaged trees occurred between summer and fall. Also, tree damage occurs at varying heights along the stem, depending on the harvest systems (Han 1997). For example, helicopter logging produced damage high on the bole (5.4 m), followed by skyline (2.0 m), CTL (1.6 m), and tractor logging (0.9 m). Moreover, one distinctive characteristic of redwood trees is that a proportion of trees occur as a clump (O’Hara et al. 2015). This clumpy growth pattern may make it difficult to use mechanical harvesting equipment to thin stands without producing a large amount of damage to the cambium.

1.4- Objectives

This study was conducted on two sites to provide a range of different tree sizes and species compositions. Thinning operations were performed by operators with different levels of work experience. Thus, our study was not intended to be able to compare sites statistically, but to examine a range of stand impacts possible from CTL harvest operations. Consequently, the goals of this study were to (1) expand the knowledge of the degree of soil compaction when soil moisture is high from CTL thinning operations (2) determine tree scar characteristics and distribution, (3) determine differences in scar size between individual trees and clumps of trees, (4) review key factors that affecting soil compaction and stand damage, and (5) recommend practices to reduce damage to soils and residual trees in two different redwood forests.

MATERIALS AND METHODS

2.1- Site description

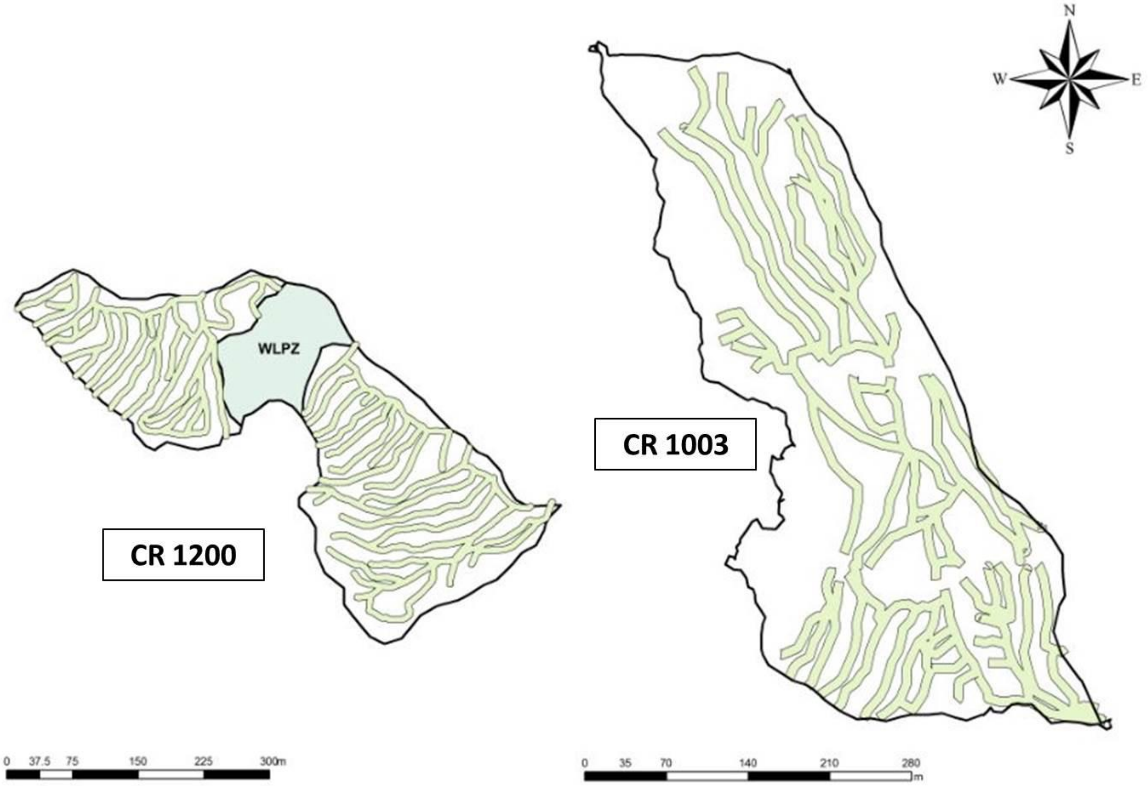

Figure 1. Map of the study sites and the forwarding trails used by cut-to-length (CTL) systems.

The commercial thinning operations were performed in two harvest units (Figure 1). Harvesting occurred in two areas of the Crannell tract, Green Diamond Resource Company forests in northern California, on roads CR 1200 (41°01'27"N, 124°05'50"W) and CR 1003 (41°01'27"N, 124°05'03"W) in the United States. Before the thinning, CR 1200 was 10.1 ha including 1.2 ha within a watercourse and lake protection zone (WLPZ) at an elevation of 126 m with a flat slope (approximately 0%), and CR 1003 was composed of 12.1 ha at an elevation of 188 m and with a ground slope ranging from 0 to 27%. CR 1200 was harvested from January to April (winter) and the other stand (CR 1003) was harvested from June to August (summer) using CTL systems. Precipitation during harvesting at CR 1200 was 896 mm and only 17 mm at CR 1003.

The soil at CR 1200 was primarily silt loam and having 12-14% organic matter. Soil in the CR 1003 unit was predominately loam. The site had 12-17% soil organic matter (Table 1). The soil classification in both units was Ultisols. These two stands were originally selected to provide a range of soil moistures but stand CR 1200 had an average moisture content of 53% and stand CR 1003 had an average of 45% soil moisture during harvesting which was not a great enough difference to provide for a statistical comparison.

Table 1. Soil particle size distribution, organic matter, and gravimetric moisture content within each harvest unit in northern California (*n* = 18).

	Soil texture (%)			Organic matter (%)			Moisture contents (%)		
Units	Sand	Silt	Clay	0-5 cm	10-15 cm	20-25 cm	0-5 cm	10-15 cm	20-25 cm
CR 1200	37	56	7	14	13	12	58	52	51
CR 1003	38	46	16	17	15	12	49	41	45

Detailed information of stand characteristics and species distribution for both units is shown in Table 2. There were 2,390 trees per hectare (TPH), with redwood being the dominant species, followed by red alder (*Alnus rubra* Bong.), Douglas-fir, and Sitka spruce (*Picea sitchensis* (Bong.) Carrière) in CR 1200. Unit CR 1003 had an average DBH of 21 cm and average tree height of 19 m, and dominated by redwood as well as red alder, Sitka spruce, and Douglas-fir. Moreover, some trees in both CR 1200 and 1003 already had bear damage.

Table 2. Stand composition characteristics including average DBH, height, trees per hectare (TPH), basal area (BA) and tree species distribution before thinning.

Units	DBH (cm)	Height (m)	TPH[a]	BA (m^2/ha)	RW	DF	RA	SS
CR 1200	20	19	2,390	99	77	5	17	1
CR 1003	21	19	1,970	92	61	10	17	13

Note : [a]Only includes trees 5 cm or greater in diameter at breast height (DBH).
[b]Percentage based on number of trees, RW: redwood, DF: Douglas-fir, RA: red alder, SS: Sitka spruce.

2.2- Harvesting equipment

In unit CR 1200 harvesting of the coastal redwood forests was done using a Ponsse Bear harvester with a Ponsse H8 harvester head (weight 24,500 kg) used to fell, delimb and buck the trees. In unit CR 1003, another harvester (Ponsse Ergo), with Ponsse H7 harvester head, was used (weight 21,500 kg). Each unit had a different equipment operator: the operator harvesting CR 1200 had more than 20 years of experience while the operator in CR 1003 only had five years’ experience. The forwarding operation was performed by the same machine called Ponsse Buffalo with the same driver from each unit. The weight of the forwarder was 14,150 kg and it could haul a load weighing up to 14,000 kg.

2.3- Thinning prescription

The objectives of thinning were to: (1) remove dead trees (2) increase tree spacing, and (3) reduce fuel continuity. In addition, the operators were directed to not cut trees larger than 60 cm in DBH while maintaining at least 60% canopy coverage. Also, healthy and vigorous dominant and co-dominant trees were retained, leaving a basal area (BA) of 23 m^2 per hectare. In addition, the operators were directed to use the logging residues to buffer the soil from soil compaction during harvest operations.

2.4- Data collection

Soil bulk density (BD)

I collected soil samples to characterize soil physical properties (soil texture, moisture contents, and BD). Soil samples were collected from the 0-5, 10-15, 20-25 cm depths in the mineral soil. Before collecting soil cores, the logging residues and forest floor were removed to locate the top of the mineral soil. BD cores were collected on a 3.6 m transect which spanned the forwarder trail at 150 m intervals. Soil cores were collected in one of the wheel tracks, at centerline, and 2 m away from the track (reference point) (Figure 2). I 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 transport from the field to laboratory. In the laboratory, soil samples were weighed, dried at 105℃ for 24 hours in the oven, and reweighed. Samples were weighed to the nearest 0.01g. A total of 33 transects were installed and 297 samples collected in CR 1200. In CR 1003, I installed 31 transects and collected 279 samples.

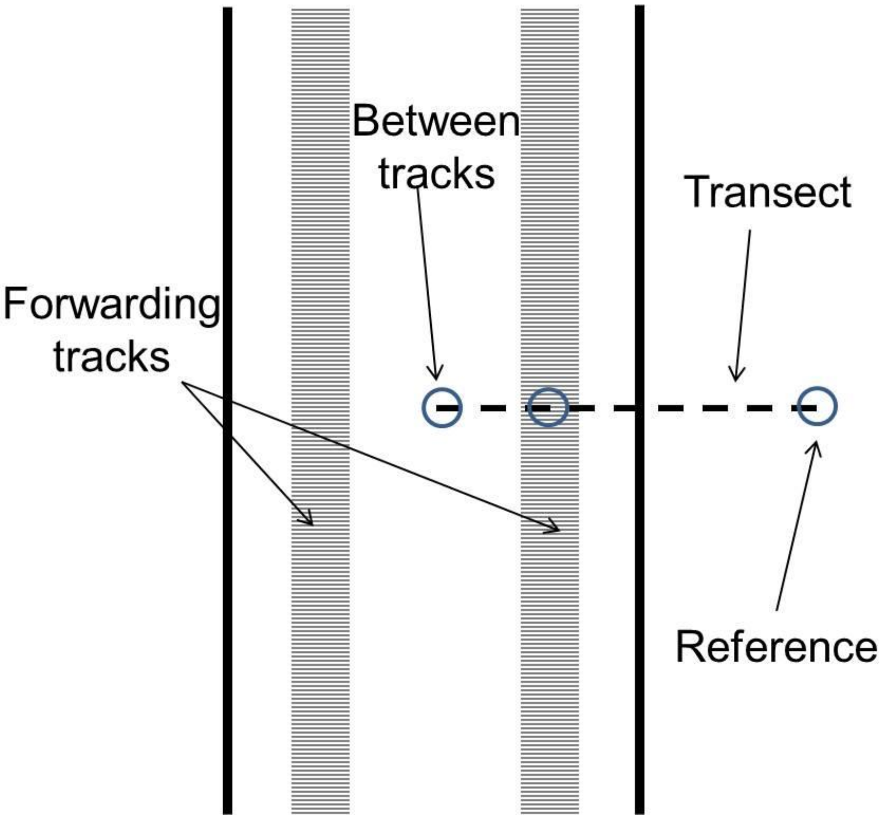

Figure 2. A diagram showing sample point location (tracks, centerline, and reference point) along the forwarding trails.

Hydraulic conductivity (HC)

In addition to the BD cores, a mini-disk infiltrometer (Decagon Device, Pullman, WA) with a diameter of 3.1 cm was used to measure the infiltration with the suction rate adjusted to 2 cm. The data were collected adjacent to each BD sample point. Infiltration measurement was only performed on the mineral soil surface. I recorded water volume every 30 seconds for a total of 300 seconds. Based on the mini-disk data, I calculated HC using the following equations, and the cumulative infiltration rate over time. The results were fitted using several functions (Zhang 1997; Decagon Devices 2013).

$$I = C_1 t + C_2\sqrt{t} \tag{1}$$

where I is the cumulative infiltration, C_1 (m/s) and C_2 (m/$\sqrt{s}$) are parameters. C_1 is related to hydraulic conductivity, and C_2 is the soil sorptivity. The hydraulic conductivity of the soil (k) is computed from

$$k = \frac{C_1}{A} \tag{2}$$

$$A = \frac{11.65(n^{0.1} - 1)e^{7.5(n-1.9)\alpha h_0}}{(\alpha r_0)^{0.91}} \tag{3}$$

where C_1 is the coefficient of the cumulative infiltration curve versus the $\sqrt{t}$, and A is a value relating the van Genuchten parameter for a given soil type to the suction rate. Soil van Genuchten parameter are n and α, r_0 and h_0 is the disk radius, and suction rate at the disk surface. I used the van Genuchten parameters developed by Carsel and Parrish (1988) for my soil texture classes.

Forwarding trails measurements

After harvesting, forwarder trail width and length data were collected by walking each trail with a GPS unit (Garmin Schaffhausen, Switzerland). The width of each trail was measured every 20 m to determine average trail width. Width and total length of trail were used to determine trail coverage within each harvest unit. I mapped each trail from the log landing using ArcGIS 10.4.1 (Redlands, CA) to determine the number of transects needed for soil samplings. This information is used to determine the relationship between the number of passes and BD and is used instead of counting the number of machine passes manually; as the distance from landing site increases, the number of machine passes decrease (Han et al. 2009).

Logging residue measurements

Slash amounts were estimated by downed woody debris survey method using the Brown transect method (Brown 1974), and allometric equations (Jenkins et al. 2004; Kizha and Han 2015). I assumed that 90% of the logging residues from the thinning operation would be concentrated on the trails based on visual observation (Figure 3). Our estimates were on a green ton basis and I assumed that logging residues have approximately 50% moisture content and converted to kg.

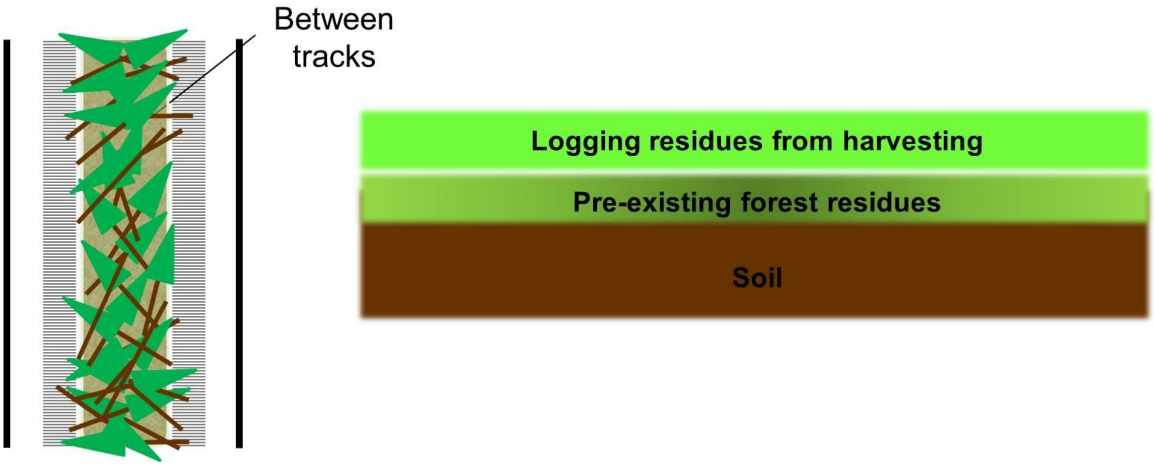

Figure 3. A diagram of logging residue on the forwarding trails.

Residual stand damage

Before data collection, I defined tree damage as the removal of the bark and cambial layer, exposing sapwood (Han 1997). I used a systematic sampling method since this method gives similar results to total tree sampling, providing an equal probability of selecting a damaged tree (Han 1997). I installed a fixed circular plot (0.04 ha in size) perpendicular to the forwarder trails every 106 m to select the sample trees, and counted tree damage. Only scars on the tree stem (not branches) were assessed. Number of scars per tree, number of trees damaged per hectare, height of scar from ground level, distance from the scar to the forwarding trail centerline, and scar size (width and length) were recorded (Figure 4). Furthermore, I distinguished between tree growth forming (individual or clump). Scar location was recorded as either: (1) facing the forwarding trail, (2) rotated clockwise from the trail, (3) opposite to the trail, or (4) rotated counter-clockwise from the trail. I did not count or measure trees (or scars) that had existing bear damage. Therefore, my data is not confounded by these pre-existing scars. All CTL produced scars were measured regardless of size.

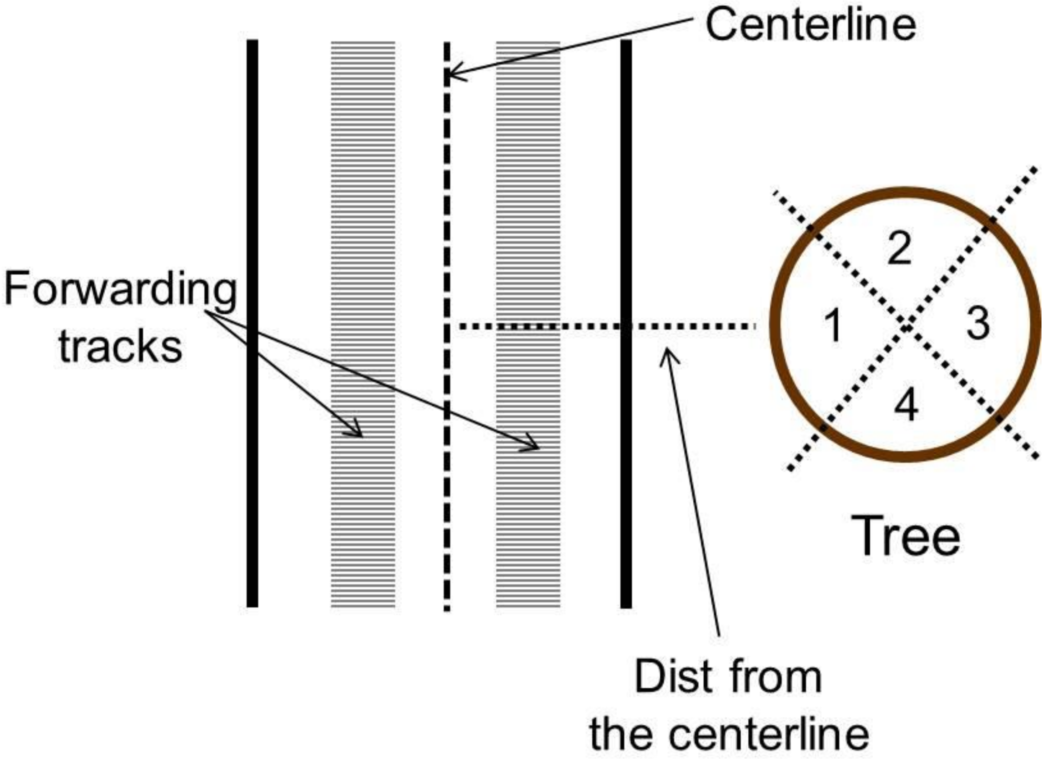

Figure 4. A view of damaged trees from above.

Statistical analyses

Data analysis was conducted using Statistical Package for the Social Sciences 24 (SPSS, Armonk NY), and R Package (R Development Core Team 2008). I tested for normality using the Shapiro test before comparing sampling locations for soil and scar damages. The analysis of variance (ANOVA) test was performed to identify the interaction of BD between sampling locations and soil depth in each unit, and the interaction of scar width between tree species and DBH, and units and tree species, respectively, in stand damage. Kruskal-Wallis test was used for multiple comparisons to compare the level of soil compaction (BD and HC) among three sampling locations: track, center, and reference at each depth. The Mann Whitney U-test was used to determine scar size differences among tree clumps and individuals. All analyses were conducted at α of 0.05.

RESULTS

4.1- Stand characteristics after thinning

Post-thinning stand characteristics in both units are summarized in Table 3. After thinning, 67% of the trees were harvested in CR 1200, leaving 768 TPH, and reducing BA to 40 m^2/ha. In this unit, the average DBH significantly increased after thinning, but height was similar. In CR 1003, 74% of trees were thinned and the residual stand had an average of 28 cm DBH and 19 m height. There were no significant changes in tree species distribution in either unit.

Table 3. Post-thinning stand characteristics of DBH, height, trees per hectare (TPH), basal area (BA), and tree species distribution.

Units	DBH (cm)	Height (m)	TPH[a]	BA (m^2/ha)	RW	DF	RA	SS
CR 1200	23	19	768	40	79	4	15	2
CR 1003	28	19	509	40	73	9	11	7

Note : [a]Only includes trees 5 cm or greater in diameter at breast height (DBH).
[b]Percentage based on number of trees, RW: redwood, DF: Douglas-fir, RA: red alder, SS: Sitka spruce.

4.2- Degree of soil compaction on the forwarding trails

There was not a significant interaction of depth and sampling locations, therefore, I will explore the main effects (Table 4).

Table 4. Summary of two-way ANOVA results showing degrees of freedom (DF), F statistics, and *p*-value for main effects and interactions for BD measurements in each unit.

	CR 1200			CR 1003		
Source	DF	F	*p*-value	DF	F	*p*-value
Depth	2	100.51	< 0.0001	2	33.10	< 0.0001
Location	2	7.09	0.0009	2	7.27	0.0008
Depth*Location	4	0.68	0.6064	4	0.22	0.9284

For all samples points (track, center, and reference points), I found the lowest BD in the surface mineral soil (0-5 cm depth). In CR 1200, the reference point, average BDs were 0.69, 0.98, and 1.09 Mg/m^3 at the 0-5 cm, 10-15 cm, and 20-25 cm depths, respectively (Table 5). At both the 0-5 cm and 10-15 cm, there were significant differences between the track and reference points, but no significant differences between the track and center point at these same depths. At the 20-25 cm depth, there was no significant difference among three locations. In CR 1003, the BDs were 0.71, 0.91 and 0.99 Mg/m^3 for the reference points at 0-5 cm, 10-15 cm, and 20-25 cm respectively. At this site, the track had significantly higher BDs as compared to the center and the reference point and there were no significant differences between the center and the reference for the 0-5 cm depth. In addition, there were no significant differences between track and center at 10-15 cm and 20-25 cm soil depths. When evaluating the percent increases in BD for each depth, I found that the largest BD increase was in the surface soil: 25.5% in CR 1200 and 30% in CR 1003 (Figure 5), and the percent change in BD decreased with soil depth. I also tested the relationship between BD and distance from the log landing, assuming that the machine passes increased as the distance from the landing decreased, however, there was no (*r* = 0.13 in CR 1200) or weak (*r* = 0.39 in CR 1003) relationships between the distance from landing and BD (Figure 6).

Table 5. Mean (± standard deviation) bulk density (Mg/m^3) collected from track, center, and reference. The same letters indicate no significant difference at each depth within each unit.

Units	Soil depth (cm)	n^*	Track	Center	Reference	*p*-value
CR 1200	0-5	33	0.83 ± 0.24^{a}	0.80 ± 0.18^{a}	0.70 ± 0.17^{b}	0.0100
	10-15	33	1.08 ± 0.13^{a}	1.04 ± 0.14^{ab}	0.98 ± 0.16^{b}	0.0330
	20-25	33	1.14 ± 0.14^{a}	1.13 ± 0.18^{a}	1.09 ± 0.17^{a}	0.6664
CR 1003	0-5	31	0.84 ± 0.22^{a}	0.71 ± 0.23^{b}	0.71 ± 0.25^{b}	0.0493
	10-15	31	1.05 ± 0.22^{a}	0.92 ± 0.26^{a}	0.91 ± 0.27^{a}	0.0611
	20-25	31	1.06 ± 0.20^{a}	0.99 ± 0.22^{a}	0.99 ± 0.23^{a}	0.2497

Note : *The number of transects.

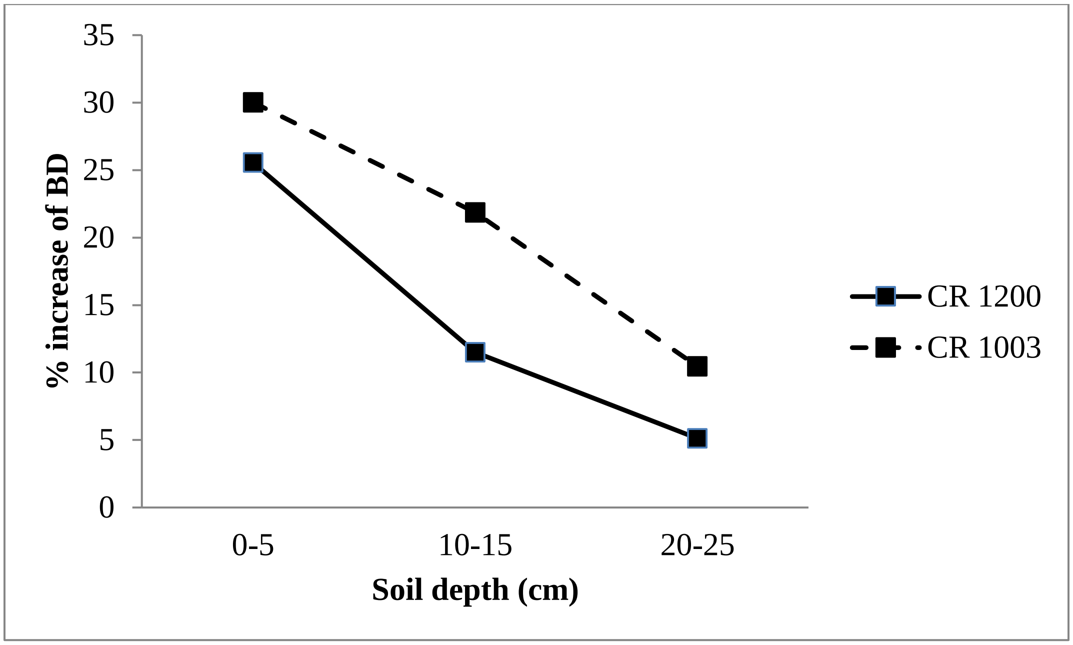

Figure 5. Percent increase of bulk density on the track after harvesting at each soil depth in each unit.

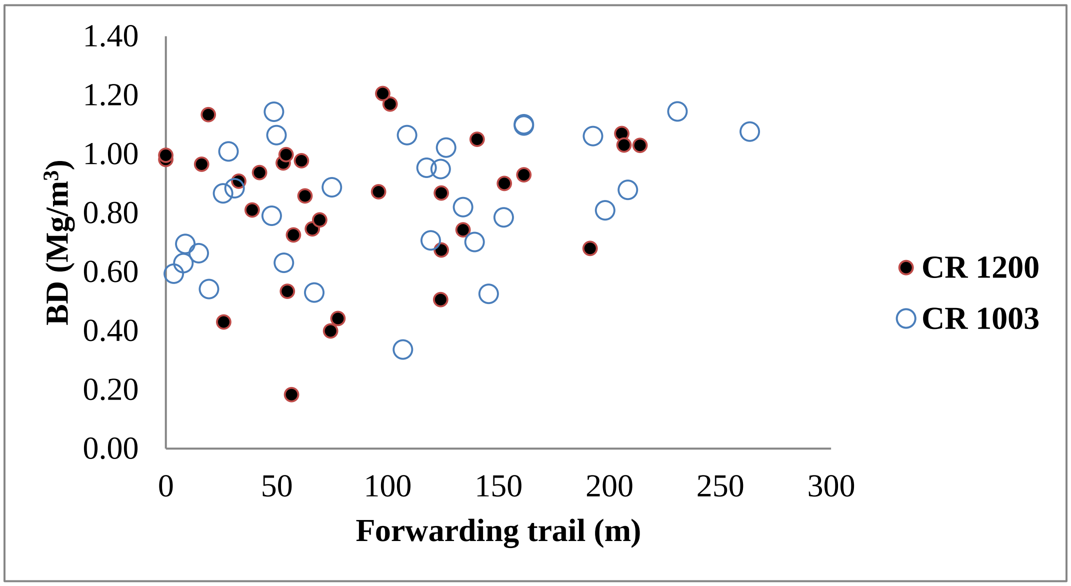

Figure 6. Relationship between distance along the forwarder trail from the log landing and bulk density.

Reference point HC was 1.25 cm/hr in unit CR 1200 and only 0.31 cm/hr in unit CR 1003, but with relatively high standard deviations (Table 6). In CR 1200, HC on forwarding track is lower than that of the reference point, but the differences were not significant (*p* = 0.6579). In CR 1003, however, there was a significant difference on HC between track and reference point. In both units, there was no significant HC difference on between track and center.

Table 6. Mean values (± standard deviation) for hydraulic conductivity (HC) (cm/hr) collected from track, center and reference at 0-5 cm soil depth. The same letters indicate no significant difference within each unit.

Units	n^*	Track	Center	Reference	*p*-value
CR 1200	33	1.17 ± 1.43^a	1.87 ± 2.78^a	1.25 ± 1.48^a	0.6549
CR 1003	31	1.51 ± 2.05^a	0.82 ± 1.48^{ab}	0.31 ± 0.53^b	0.0222

Note : [*]The number of transects.

4.3- Description of residual stand damages

On unit 1200, winter harvesting resulted in 16.2% of the trees scarred by CTL operations. These trees had an average DBH of 24.8 cm with an average of 1.7 scars per tree (Table 7). Although there were very few red alder trees remaining after thinning (Table 3), they greatest number of scars (approximately three scars per tree), redwood had more than one scar regardless of growth forming, and Douglas-fir and Sitka spruce had minor scarring (Table 8). On all the trees in unit CR 1200, the average scar was 9.0 cm wider, and 27.3 cm long with scars occurring 4.8 m from the centerline of the forwarding trails at a height of 1.3 m from the ground level (Table 9). Over 60% of the scars had a width less than 10 cm and length than 40 cm which was greater than CR 1003 (Figure 7). The majority of scars were located within 2 m of the forwarding trail and less than 1 m of ground height in CR 1200.

On CR 1003 during summer logging, 32.2% of trees were damaged. Trees with scars averaged 30.7 cm DBH and had 1.7 scars (Table 7). Sitka spruce and Douglas-fir had the greatest number of scars with an average of more than two (Table 8). Redwood and red alder had an average of more than one scar. Overall, scars in this unit averaged 10.4 cm wider and 36.1 cm long (Table 9). Scarred trees were located 4.5 m from the centerline of forwarding trails with scars located 1.5 m above ground level. More than 60% of the scars were wider than 10 cm and less than 40 cm long (Figure 7). The majority of scarred trees were generally located within 4 m of the forwarding trail and 34% of scars were located less than 1 m of ground height.

Table 7. Summary of residual tree scars resulting from CTL operations in each unit.

Units	% damaged tree[a]	Total[b]	RW	DF	RA	SS	DBH of damaged trees (cm)	# of damaged trees per ha	# of scars per tree
CR 1200	16.2	96	81	5	10	0	24.8	108	1.7
CR 1003	32.2	150	99	24	19	8	30.7	139	1.7

Note : [a]Calculated based on all scar sizes. Value represents the ratio from total number of sampled trees.

[b]RW: Number of damaged trees, RW redwood, DF: Douglas-fir, RA: red alder, SS: Sitka spruce.

Table 8. Number and percent of scars per tree for each tree species[a].

	# of scars per trees				Damaged trees[b] (%)			
Units	RW	DF	RA	SS	RW	DF	RA	SS
CR 1200	1.5	0.4	2.9	0.0	20	21	15	0
CR 1003	1.5	2.0	1.7	2.4	30	36	30	46

Note : [a]RW : redwood, DF: Douglas-fir, RA: red alder, SS: Sitka spruce

[b]Calculated damaged trees divided by undamaged trees in each species.

Table 9. Summary of scar characteristics from CTL thinning for each unit.

Units	Scar width (cm)	Scar length (cm)	Distance from centerline (m)	Height from ground (m)
CR 1200	9.0	27.3	4.8	1.3
CR 1003	10.4	36.1	4.5	1.5

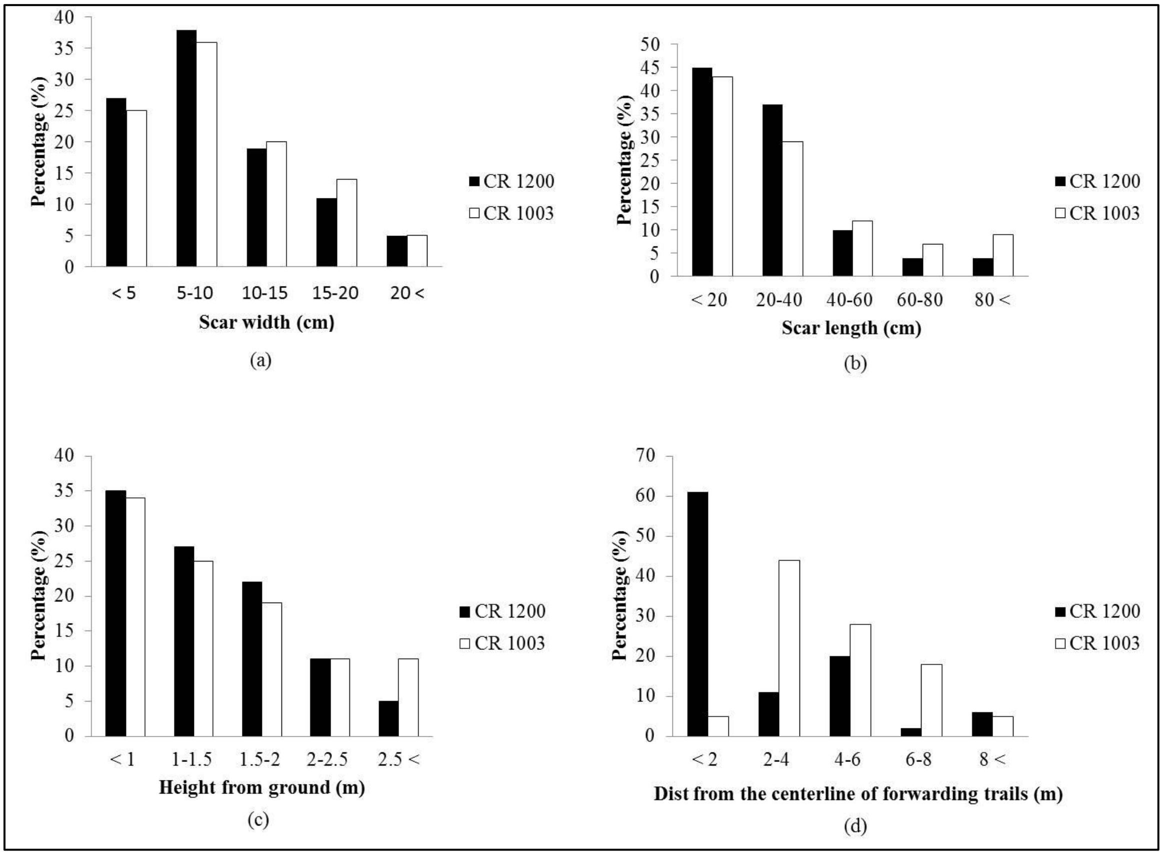

Figure 7. Average scar distribution (percentage) of all tree species combined as related to width (a) and length (b), height from ground level (c), and distance from centerline of forwarding trails (d) for each unit.

In CR 1200, 38% of scars were facing the trail, with the fewest scars located opposite the trail. In addition, I compared scar size according to tree growth form in which there was a slight difference of scar width between clump and individual trees in CR 1200 (Table 11), but they were not statistically different ($p > 0.05$). However, scar length in clump trees was almost twice as that of individual trees ($p < 0.05$). In CR 1003, the scars were 3 cm wider and 15 cm longer in clump trees as compared to individual trees and were statistically different for both width and length ($p < 0.05$).

Table 10. The number of scars and percentage distribution in each location by quadrants for clumps and individual trees in each unit.

Units	Scar location	Clump	Individual	Total	Percentage (%)
CR 1200	# 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
CR 1003	# 1	30	69	99	38
	# 2	13	41	54	21
	# 3	20	34	54	21
	# 4	21	30	51	20
	Total	84	174	258	100

Table 11. Mean scar size (width and length) of individual and clumped trees in each unit.

	Width (cm)			Length (cm)		
Units	Individual	Clump	*p*-value	Individual	Clump	*p*-value
CR 1200	8.1	9.1	0.1611	16.7	28.1	0.0001
CR 1003	9.5	12.2	0.0054	31.3	46.2	< 0.0001

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

DISCUSSION

5.1- Soil compaction

Soil bulk density (BD)

I detected BD differences between the wheel track and reference point in the surface mineral soil (0-5 cm) in both units and as soil depth increased, the difference between the two values decreased. Han et al. (2009) reported similar results showing that a significant difference was detected in the surface mineral soil, however, they could not detect difference as soil depth increased when using CTL systems on ashy loamy soil in the Inland Northwest, United States. In a study on sandy loam soils, McNeel and Ballard (1992) reported that averaged pre-harvest bulk densities were 0.71, 0.82, and 0.87 Mg/m^3 at 10, 20, and 30 cm soil depths, and increased to 0.85, 0.92, and 0.99 Mg/m^3, respectively with intense traffic by using CTL system. McDonald and Seixas (1997) found that in the mineral soil (0-5 cm depth), BD was significantly greater regardless of slash amount, but, there were no significant BD increases at the 15-20 cm soil depth on loamy sand with no vegetative cover. They also noted that the percentage BD increase was highest at 0-5 cm of soil depth and decreased with soil depth. In our study, there was not a large percent increase (25% and 30%) in either unit at the 0-5 cm soil depth. Han et al. (2009) showed that when using CTL system on volcanic ash-cap soil with a loamy texture that almost 30% of BD increase was observed at 7.5 cm. In addition, soil moisture contents at our sites were higher than other studies, ranging from 49 to 58%. Han et al.

(2009) showed that soil moisture is a significant factor affecting the soil compaction in CTL system.

The greater increase of BD at the soil surface may be associated with the low initial BD values. For example, Williamson and Neilsen (2000) reported that a greater percent increase of BD was detected on fine-textured soils with low initial BD. In this study, there was a negative relationship between initial BD and the percent increase of BD (Figure 8) and is similar to the findings of Page-Dumroese et al. (2006). Ampoorter et al. (2012) also suggested if soil BD before harvesting is higher, then the change in BD may be only a slight increase. A negative correlation between absolute BD increase and BD before traffic at 10, 20, and 30 cm soil depth in sand and clay soil was also shown and implied that machine passes had little effect on already compacted soils. Also, in the models developed by Han et al. (2009), they predicted soil BD changes with 25-30% moisture content which provides one method for determining soil impacts before logging operations begin.

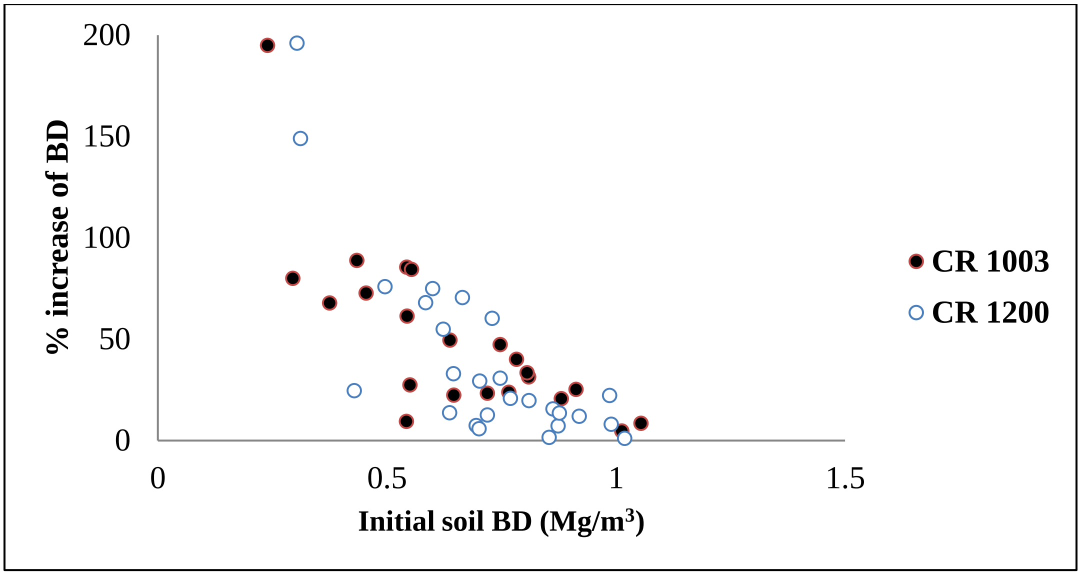

Figure 8. The relationship between initial bulk density and percent increase of bulk density.

Hydraulic conductivity (HC)

Generally, as BD increases, water infiltration into the soil profile decreases because of reduced macropore volume (Jansson and Johansson 1998; Wolkowski and Lowery 2008; Han et al. 2009). We found no significant differences in HC among three forwarding trail locations in CR 1200, and unexpectedly, there was a significantly higher HC on track compared to that on off-track in CR 1003. Greacen and Sands (1980) reported that compaction may not necessarily alter micropores volume, the unsaturated HC may be unaffected or even increased. Although I found significant changes in BD between compacted and un-compacted area, the porosities are likely still high despite machine trafficking. Rose (2013) suggested HC of the soil is strongly affected by detailed pore geometry and water content. Therefore, it is recommended to conduct soil porosity analyses for more details on expected changes in HC.

One question about increased compaction has been how fast soils will recover. This can be a complex question and dependent on the degree of compaction, soil organic matter content, the presence of a freeze-thaw cycle, shrink-swell, root growth, and belowground fauna movement (Vanderheyden 1981; Froehlich and McNabb 1984). Page-Dumroese et al. (2006) indicated that on coarse-textured soils, compaction recovery can be relatively quick (within five years), but on fine-textured soil recovery may take decades to recover to pre-disturbance levels. Previous logging on my site occurred 30 years ago and I could still detect a few old skid trails before the current logging operation. This indicates that, although some recovery from past logging may have occurred, some level of compaction was still present and some was likely masked by the increasing forest floor. Although fast recovery can occur from deep soil profile freezing (Mace 1971), the climatic conditions in the northern California coastal redwood zone is more prone to heavy rains with soil temperatures usually above 0℃. This indicates that any increases in compaction or decrease in HC from the harvest may not readily recover. However, we could find no data about earthworm movement or root growth in this area which may have help mitigate compaction or increase soil porosity.

Although HC is usually used as a method to understand the impacts of soil compaction, it is less reliable than collecting BD cores. This is because HC data often has large standard deviations. Huang et al. (1996) suggested that the lack of significant differences in infiltration could be due to this high spatial variability, but it could also be that I collected an insufficient sample size. Nielsen et al. 1973) suggested the true variation in water movement that exists from place to place in any area should be examined with large number of samples. We estimated HC from 31-33 transects within a 10 to 12 ha area making it difficult to ensure that our HC samples fully explain each sample locations (track, center, reference) and site variability.

Factors affecting soil compaction

CTL harvesting is known to produce a heavy slash mat which can influence the degree and extent of compaction (McNeel and Ballard 1992; McDonald and Seixas 1997; Han et al. 2006; Han et al. 2009). The equipment operator created a large amount of logging residues to prevent soil disturbance with my study area (Table 12). Usually, logging residues are weighed to determine the total amount remaining (Han et al. 2006), however, we had sawlogs and a large amount of branches, twigs, and stems that could not be adequately weighed. Therefore, we used two methods to determine how much logging residues were present. On volcanic ashy-cap soil with loamy texture, Han et al. (2009) noted that the degree of soil compaction when using CTL was severe when the soil was exposed as compared to areas covered in logging residues. They also noted that the actual amounts of residues were not important; only that the mineral soil was buffered from direct contact with equipment. Furthermore, McMahon and Evanson (1994) reported that changing the amounts of logging residues altered the amount of compaction on loamy sands: a 16% increase in BD was noted on sites with heavy logging residues (18.6 kg/m^2), 21% increase with light (9.2 kg/m^2), and 25% on bare ground. However, the mitigating effects of logging slash can be reduced depending on the size of the material (McDonald and Seixas 1997; Han et al. 2006). Han et al. (2006) reported that small diameter slash was likely to be crushed so it could not absorb the tire pressure. Also, the amount of logging residues was more effective on wet soil than on dry soil, suggesting an interaction between moisture content and logging reside amounts. Plentiful logging residues on wet soils likely minimized the amount of soil compaction on my sites. McDonald and Seixas (1997) also confirmed that logging residues had a more significant effect on wet soil compared to dry when using a log forwarder, suggesting that as the moisture content increases the bearing capacity of the soil decreases. Thus, the large quantities of logging residues on the soil surface likely significantly reduced equipment impacts on the mineral soil even though our soils were relatively wet.

Table 12. Amount of slash covered on the forwarding trails.

Units	Pre-thinning (kg/m^2)	Post-thinning (kg/m^2)	Total (kg/m^2)
CR 1200	2.3	29.8	32.1
CR 1003	8.2	17.1	25.3

Within the mineral soil, the amount of organic matter may also affect how equipment impacts the amount of soil compaction (Froehlich and McNabb 1984; Dexter 2004). Ares et al. (2005) suggested large areas of forest soils in Pacific Northwest are covered with high organic C soils which have a relatively low BD which minimizes equipment impacts on forest site productivity. Coastal redwood sites in our study have a large amount of soil organic matter from understory inputs, over-story tree litterfall, and slow decomposition rates associated with cool, moist climates (Froehlich and McNabb 1984). Williamson and Neilsen (2000) found a negative relationship between BD and organic matter, showing high r^2 value (0.85) regardless of the number of machine passes. They also reported that BDs in wet conditions were lower than those in dry conditions as machine passes increased (0.9-1.0 Mg/m^3 vs. 1.2-1.4 Mg/m^3), suggesting that the soils in low rainfall areas with lower organic matter contents had highest BDs, while soils in high rainfall units, with higher organic matter contents had lowest BDs.

One other factor that can affect the amount of soil compaction is the number of equipment passes or the distance from log landing to the location of the sample point. To determine if this was a factor on our two units, I used a Pearson’s correlation to test the relationship between the distance from landing and BD in the surface mineral soil (0-5 cm depth). Unlike previous studies (McDonald and Seixas 1997; Han et al. 2009), there were no clear relationships between distance from landing site and BD (Figure 3). Although Han et al. (2009) could evaluate the differences of soil compaction using distance from log landing in CTL logging operations with a negative coefficient at 25-30% moisture content, the operator on my study sites made short forwarding trails and therefore fewer machine passes which may explain the lack of relationship between BD along the trails (Figure 1). This unit layout scheme coupled with the abundant logging slash on the trail surface likely buffered the site from greater soil impacts.

I could not measure the machine characteristics in the fields (e.g., ground pressure, or equipment speed). However, one characteristic of the equipment was the use of bogie-track with the harvester and forwarder. Bogie- tracks are used to disperse the load to a greater area so it is not concentrated into small area on the soil surface. This can be effective for minimizing ground pressure compared to using the conventional wheeled equipment (Bygdén et al. 2004; Gerasimov and Katarov 2010). In a previous study, bogie-tracks produced less soil rutting damage and did not raise the resistance to soil penetration compared to wheel-tracks (Bygdén et al. 2004).

The extent of compaction on forwarding trails

Unlike WT harvesting operations where equipment travels over the entire unit, we could detect the forwarding trails due to repetitive movement. Unit CR 1200 had the center points of forwarding trail compacted, but we did not find similar impacts in unit CR 1003. Equipment trafficking across the centerline of the trail causes the center point to increase in compaction. In unit CR 1200, 18.8% of the unit was in trail systems with a similar amount compacted. In unit CR 1003 16.5% of the area was in trails, but only 8.3% was compacted suggesting that the different operators moved over the forwarding trails dissimilarly (Table 13). McNeel and Ballard (1992) calculated that forwarding trails accounted for 19.7 % of the unit whereas Lanford and Stokes (1995) reported that 53% of the soil was in trails when using a CTL system. These previous studies examined the entire trail area. Han et al. (2009) suggests a different calculation which distinguishes between the centerline and the track. When using these different parameters, they reported that although approximately 19-20% of total harvesting unit was covered by trails from CTL system, only 10% of the area was compacted in the wheel track. This is an important consideration when determining the areal extent of trails, their impact on water movement within and off-site, and the amount of restoration activities that may have to occur if soil standards for industry or public lands are exceeded.

Table 13. Average trail width, trail area, and expected compacted area from CTL system.

		Trail width		Trail area in the units		Compacted area	
Units	Area (ha)	*n*	Mean (m)	ha	%	ha	%
CR 1200	10.1	162	3.7	1.9	18.8	1.9	18.8
CR 1003	12.1	137	4.0	2.0	16.5	1.0	8.3

Note : The trail width is composed of tracks and center area.

5.2- Residual stand damage

The factors in scar differences between two units

I analyzed each stand separately since they were harvested at two times of year, had differing stand composition, average DBH, and were harvested with different CTL equipment. On CR 1200, the harvester head was higher than the one used on CR 1003, and therefore, it generated smaller and fewer tree scars. This is likely because the larger head would be able to handle larger trees better as compared to a smaller head. Additionally, each unit had different slopes (0% vs. 0-27%). Limbeck-Lilienau (2003) noted that there is a substantial slope effect on the number and size of tree scars; more severe scarring (20-21%) on steep slope units as compared to 3-6% of trees with scars on flat ground.

Operator skill also impacts the severity of stand damage. As noted previously, the operator in CR 1200 had over 20 years of working experiences and had practiced for six months before harvesting the unit. The operator harvesting CR 1003 had worked for only five years and only had one month of training. Kelley (1983) showed that a difference in scarring of 16% occurred with different operators. In addition, Sirén (2001) found the proportion of trees damaged varied from 1.4% to 6.6% with different operators. In this study, the operator in CR 1003 was not familiar with cutting clumped trees which may have affected the number of scars in that unit.

Moreover, many studies indicate that seasons affects the amount of tree damage (Cline et al. 1991; Bettinger and Kellogg 1993; Limbeck-Lilienau 2003). Yilmaz and Akay (2008) reported that the greatest number of tree scars occurred during the summer. Bobik (2008) found that stands harvested during the winter season in Sweden had fewer scars compared to stands harvested in other seasons. Kellogg et al. (1986) measured stand damage from a skyline cable system in a western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and Sitka spruce stand and found that residual trees can be susceptible to scars during logging in the summer because the cambium and bark are loose and easily damaged.

Previous studies suggest that the scarring varies in different tree species. However, our data show that only DBH of the tree was a significant factor in the number of scars (Table 14). Although our data is limited to two units, we tested scar width for species and units (Table 15). We found that scar width was significantly greater in CR 1003 as compared to CR 1200. We also found that species was important for Sitka spruce and red alder in CR 1003, but there were differences among all species in CR 1200 (Figure 9). Aho et al. (1983) suggested that the trees which are thin-barked and non-resinous are susceptible to damage from logging. In redwood, the sapwood is not as decay-resistant as it is in other members of the *Cupressaceae* family, but it has decay-resistant bark and heartwood, and is virtually immune to insects and disease (Krokene et al. 2008). These redwood characteristics can help prevent deep scars. Froese and Han (2006) showed that scar size was different between Douglas-fir (65 cm^2) and grand-fir (*Abies grandis* Douglas ex D. Don) (425 cm^2). Howard (1996) reported that scars from cable yarding operations also varied among Douglas-fir, western hemlock, and western red-cedar (*Thuja plicata* Donn ex D. Don). Western red cedar was damaged nearly twice as much as Douglas-fir, and suggests that this species has bark thick enough to prevent scarring. In my study, however, I could not test season or operator effects separately since these two variables are confounded. Thus, we could not detect whether scar width differences in the two units and for each species were caused by different operators.

Table 14. Two-way ANOVA showing degree of freedom (DF), F statistics, and *p*-value for main effects (species and DBH) and their interaction with scar width (dependent variable).

	DF*	F	*p*-value
Species	3	1.452	0.2270
DBH	1	76.346	< 0.0001
Species*DBH	3	0.579	0.6290

Table 15. Two-way ANOVA showing degrees of freedom (DF), F statistics, and *p*-value for main effects (unit and species) and their interactions with scar width.

	DF	F	*p*-value
Units	1	8.359	0.0040
Species	3	1.323	0.2664
Units*Species	2	12.693	< 0.0001

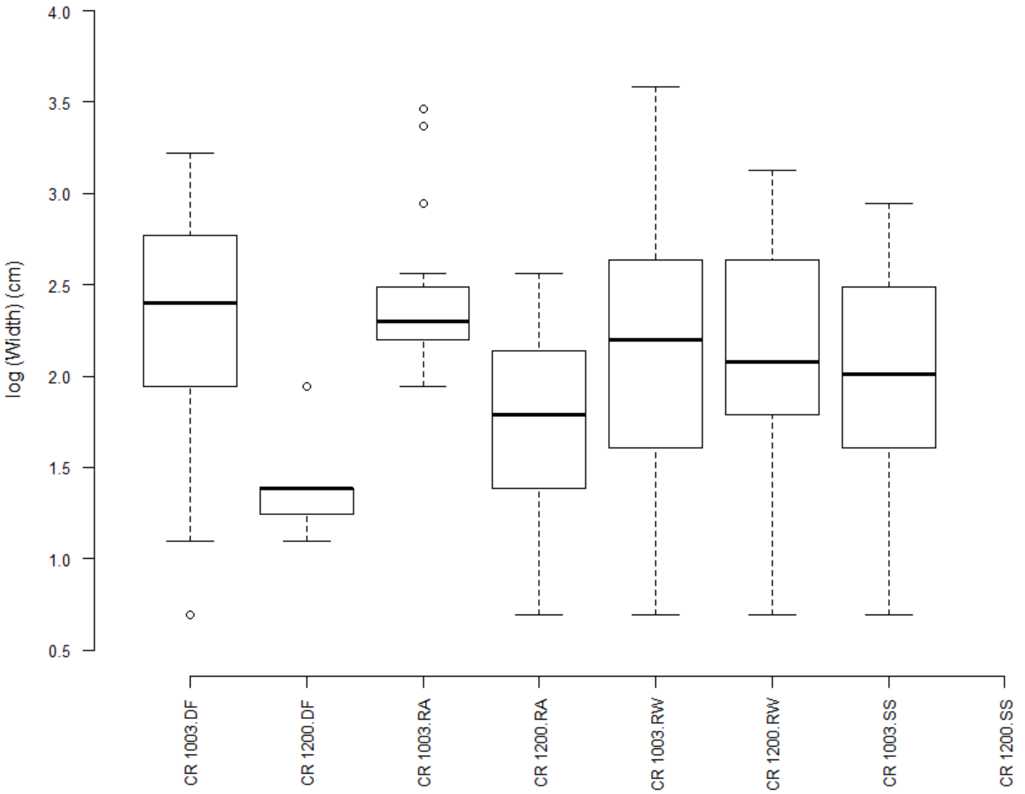

Figure 9. Scar width difference among species in CR 1200 and CR 1003 (RW: redwood, DF: Douglas-fir, RA: red alder, and SS: Sitka spruce).

Operational difference between harvesting and forwarding operation

The interval between felling and forwarding was very short in our study, therefore I could not detect the amount distribution, or size of scars attributed to each machine. Instead, I observed how each machine generated scar damage during operations. Scars on residual trees resulted from the harvester when large-sized trees were grappled or when felled trees got hung-up on residual trees. Scars from the forwarding operation occurred when logs were moved from the deck (ground) to the bunk. Both machines generated scarring low to the ground if they moved along the trees near the forwarding trails. This type of damage may make trees more susceptible to fungi infestation (Hunt and Krueger 1962). Han and Kellogg (1997) showed that a harvester caused more damage than a forwarder (63.8% vs. 28.6%), however, the forwarder caused larger scars on residual trees as compared to the harvester (178.7 cm^2 vs. 143.9 cm^2). They suggested that damage could be reduced by retaining optimal trail spacing for harvester, and making trails as straight as possible for the forwarder.

Scar differences between clumps and individual trees

I detected longer and wider scars in clumped trees as compared to single stem trees in both harvest units. When cutting trees within a clump, the harvester operator spent a long time grappling the tree since there was limited space. This would often generate larger scars on the residual trees within the clumps. When the harvester initially grabbed a clumped tree, it was slightly higher in a clump than on an individual tree because it was difficult for the harvester head to catch the lower part of the tree. This caused the harvester head to travel downward on the tree causing lengthwise scarring. Kelley (1983) found that trees in high-density stands were difficult to cut without scarring the neighbor trees. Additionally, there were some residual trees that were cut by the harvester sawblade, resulting in indirect damage. These trees can be unstable and prone to wind-throw; generating additional damage. Boe (1965) showed that a combination of wet soil and strong winds creates significant windfall damages in northwestern California. I did not count either windfall or bear damage, but found more scars from sawblades in CR 1200 as compared to CR 1003. The equipment operator working in unit CR 1003 adjusted the harvester head system so the sawblade cut only as much as the head grabbed. This likely prevented additional scarring on adjacent trees.

Scar distribution

Our data supports the work of others who have examined residual tree scars associated with CTL logging operations (Bettinger and Kellogg 1993; Han and Kellogg 2000; Froese and Han 2006; Tavankar et al. 2015). I found a majority of the scars on the residual trees were located near the ground (within 1 m) in both units. Froese and Han (2006) reported that over 30% of the scars were located within 1 m of ground, suggesting that the majority of scars came from machine passes, timber processing, and handling. Bettinger and Kellogg (1993) also found this same result and suggested that trees with scars this low to the ground may be more vulnerable to wood-decaying fungi than those with scars higher on the stem (Hunt and Krueger 1962). Nevill (1997) reported that roots and stems scarred near the ground were always infected with the decay fungi, *Heterobasidion annosum*. This fungus spreads by basidiospores or conidia in fresh wounds created by thinning operations (Stenlid 1985). Trees harvested from CR 1200 and CR 1003 had scars at many different locations on the stem. In CR 1200, the trees growing in clumps were frequently cut lower on the bole to increase the volume harvested. However, trees in CR 1003 were cut higher on the stem to have enough space for operators to cut one tree from the clump.

The majority of the scars on the stems were mainly within 4 m from the centerline of the forwarding trails in both units with only a small proportion of scars located over 4 m from the trails. This same pattern was also found by Bettinger and Kellogg (1993) and

Han and Kellogg (2000) with 64-72.2% of scars occurring within 4.5 m of trail centerline from CTL system. Athanassiadis (1997) suggested that as the distance between the operator and the tree increases, it is harder to control the both machine and logs, therefore most operators will do a majority of work near the forwarding trail.

5.3- Acceptable levels of impacts from CTL system

Soil compaction

We found an increase in BD of approximately 25-30% in the soil surface (0-5 cm depth) which was an increase in BD from to 0.83 and 0.84 Mg/m^3. Several studies have shown that increasing BD can limit the root growth (Daddow and Warrington 1983; Pierce et al. 1983). Pierce et al. (1983) suggest that BD values ranging from 1.39 Mg/m^3 in clay to 1.69 Mg/m^3 in sand and loamy sands affected root growth. The U.S Department of Agriculture, Forest Service has used a threshold of 15% increase in BD to ensure long-term soil productivity in Pacific Northwest region (Page-Dumroese et al. 2000). Changes in BD on our sites may not be severe enough to restrict the root growth in silt loam, loam, and sandy loam, but the change in BD at some locations means that it would exceed the 15% increase standard. In addition, Froehlich (1979) developed a prediction model to describe how increased BD may alter tree growth and showed that there could be a 6-12% reduction in tree growth rate depending on the degree of soil compaction. He also suggested that if BD increases more than 10%, there will also be a decrease in root growth for residual young ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson), but this change may not be great enough to limit ground-based logging. Compaction caused by a vibratory soil compactor in 3-8 year old ponderosa pine plantations did not reduce the tree growth, but soil texture is important when determining the overall growth reductions (Gomez et al. 2002). Likewise, Page-Dumroese et al. (2006) found that there is no clear correlation between compaction and future tree growth since compaction is also related to other soil impacts, such as displacement, mixing, and rutting. They also reported that using a percent increase of BD could limit activities with low initial BD and on sites with high initial BD, the changes in macropores may alter tree growth without being able to detect a BD increase.

Residual stand damage

Scar size is an important factor associated with future activity of wood decay fungi (Aho et al. 1989; Camp 2002). Specifically, scar width has been shown to be more important than length when determining fungal decay incidence (Wallis and Morrison 1975). Scar size is critical for determining how many residual trees may be damaged during CTL activities. For example, I show that if scars wider than 5 cm were counted, 13.9% of the residual trees in CR 1200 could be counted, whereas 31.5% of the trees with scars would be counted in CR 1003 (Table 16). If scars greater than 20 cm are the ones counted, then scarred trees would only amount to 1.7% in CR 1200 and 3.9% in CR 1003. This information is important for land managers to understand when determining the acceptable level of residual stand damage. The landowners of the units harvested during this study provided their definition for stand damage for redwood and Douglas-fir (Redwood: scars wider than 30% of circumference of trees, Douglas-fir: scars wider than 20% of circumference of trees; M. Carroll, pers. comm., 2017). When I calculated the percentage of damaged trees using these definitions, it resulted in approximately 5% decrease in CR 1200, and 9% decrease in CR 1003 (Table 17). Based on Table 16, these values were between 5 and 10 cm leading me to suggest that scar width between 5 to 10 cm of scar width would be a reasonable target for redwood stands in California.

Table 16. Percentage of number of damaged trees in different scar width (cm) categories.

Units	None	Wider than 5 cm	Wider than 10 cm	Wider than 15 cm	Wider than 20 cm
CR 1200	16.2	13.9	7.6	3.2	1.7
CR 1003	32.2	31.5	21.0	11.4	3.9

Table 17. Percentage of number of damaged trees and number of scarred trees for each species based on the landowner’s definition.

Units	% of scarred trees	Total	RW	DF	RA	SS
CR 1200	11.0	65	50	5	10	0
CR 1003	22.7	106	59	20	19	8

Note : RW: redwood, DF: Douglas-fir, RA: red alder, and SS: Sitka spruce.

CONCLUSIONS

This is the first CTL study in coastal redwoods in northern California to assess changes in soil properties and stand damage during times of high moisture content. Although BD on the tracks was relatively low, however, BD in the tracks increased 25-30%. HC data were inconsistent which is likely due to high soil spatial variability and I recommend more detailed measurement of soil porosities and determining both macro- and micro-porosities with a greater number of samples. When only the tracked areas of the areas of the forwarding trails are considered, the areal extent of compaction could be reduced. In addition, I found a total of 16.2% of trees were damaged in CR 1200, and 32.2% in CR 1003 and the scars were concentrated near the forwarding trails (less than 4 m), and ground level (less than 1 m). As majority of scars were found on the side of the tree that was facing the forwarding trail and resulted from machines hitting residual trees. Scar width and length are greater in trees growing in clumps than those with individual stems because the harvester operator struggled to grapple the trees in clumps due to limited space.

In northern California, the CTL system would not be detrimental to affect the future growth, however, it depends on site factors such as species, soil texture, seasons and so on. In coastal redwood stands, the following management practices are recommended:

- Move carefully by using the same trails.

- Avoid scarring trees close to the forwarding trail by placing plastic culverts or rubber materials on trees prior to harvest.
- Leave low stumps so equipment does not have to move to the side of the trail, however, leave a high stump to provide space for the harvester head when harvesting clumped trees. This may also help prevent damage from wind.
- Hire experienced operators when cutting redwood clumps since this is a specialized skill.
- Harvest in the winter, not in spring through summer.

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APPENDIX A

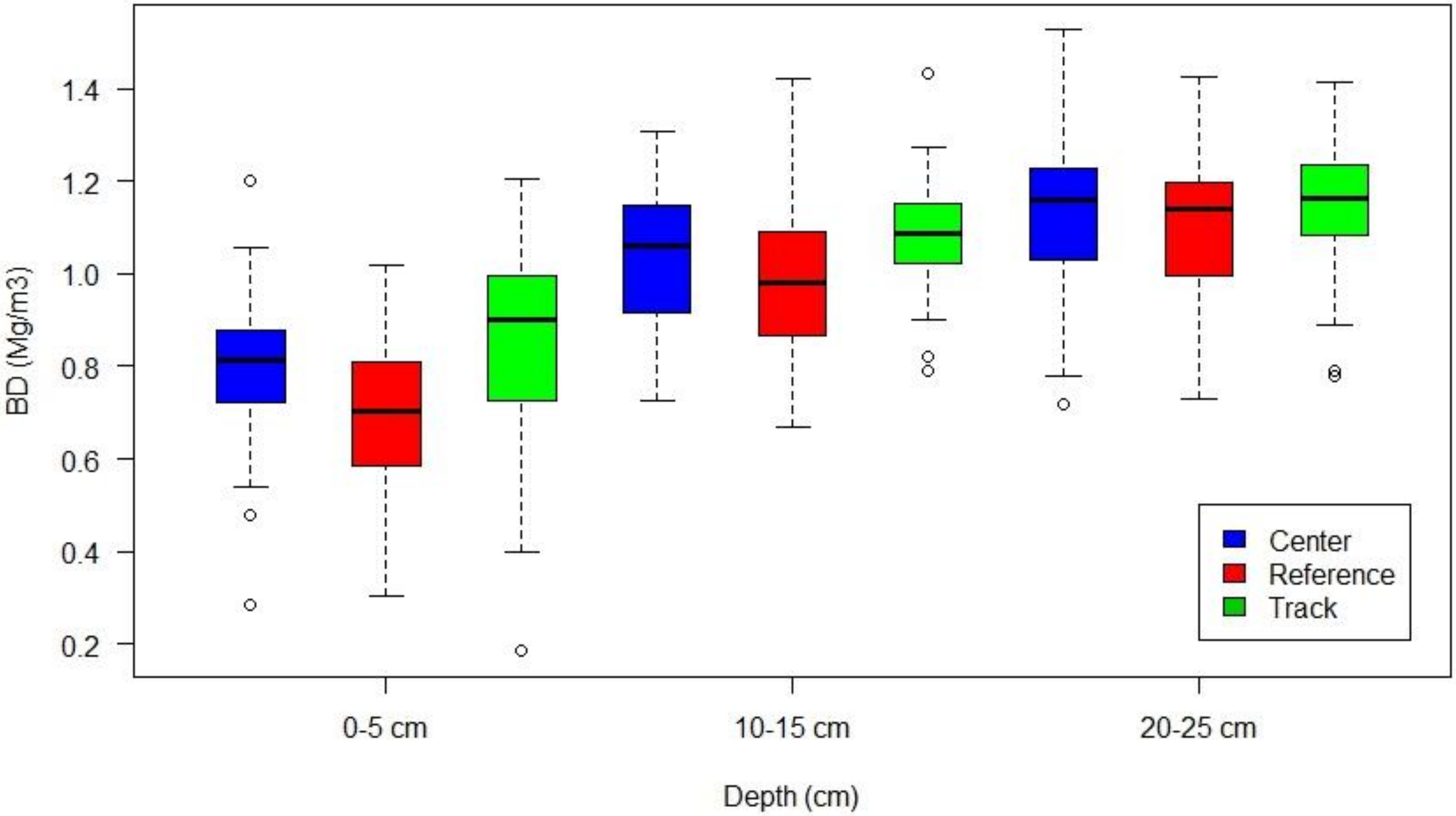
Appendix A: Raw data and boxplot of bulk density (BD) at each soil depth and sampling location in CR 1200.

# of transect	On (0-10 cm)	Center (0-10 cm)	Reference (0-10 cm)	On (10-20 cm)	Center (10-20 cm)	Reference (10-20 cm)	On (20-30 cm)	Center (20-30 cm)	Reference (20-30 cm)
1	0.97	0.76	0.81	0.91	0.95	0.88	0.78	0.88	0.77
2	1.17	1.00	0.73	0.79	0.90	0.84	0.79	0.97	0.85
3	0.93	0.75	0.77	0.93	0.94	0.84	0.89	0.78	0.82
4	1.07	0.94	0.99	1.06	0.85	0.98	1.11	1.16	1.14
5	1.03	0.91	0.92	1.04	0.86	1.02	1.40	1.05	1.31
6	1.05	0.87	0.60	0.82	0.83	0.79	0.98	0.92	0.81
7	0.75	0.81	0.69	1.09	1.19	1.07	1.09	1.09	1.08
8	0.81	0.87	0.72	1.09	0.72	0.96	1.03	1.08	1.16
9	1.00	1.06	0.86	1.15	1.21	1.42	1.18	1.24	1.33
10	0.68	0.72	0.77	1.05	0.91	1.12	1.10	1.01	1.17
11	1.03	0.57	1.02	1.44	1.25	1.37	1.41	1.39	1.42
12	0.87	0.54	0.85	1.15	0.95	1.07	1.14	1.03	1.12
13	0.44	0.88	0.55	0.90	1.10	0.67	1.03	1.17	0.97
14	0.67	0.74	0.80	1.13	0.92	0.98	1.09	1.07	1.14
15	0.86	0.86	0.65	1.15	1.07	1.06	1.18	1.17	1.15
16	0.98	0.85	0.58	1.19	1.06	0.99	1.18	1.13	1.10
17	0.87	0.74	0.50	1.02	0.94	0.93	1.03	0.83	1.00
18	0.91	0.86	0.70	1.13	1.12	0.74	1.26	1.26	1.03
19	0.43	0.48	0.56	0.90	0.87	0.71	0.93	0.85	0.75
20	0.94	1.03	0.87	1.21	1.17	1.12	1.27	1.25	1.28
21	0.40	0.77	0.62	0.93	1.14	0.95	1.26	1.21	1.22

Appendix A: Continued

# of transect	On (0-10 cm)	Center (0-10 cm)	Reference (0-10 cm)	On (10-20 cm)	Center (10-20 cm)	Reference (10-20 cm)	On (20-30 cm)	Center (20-30 cm)	Reference (20-30 cm)
22	1.13	0.81	0.67	1.27	1.15	1.15	1.33	1.22	1.19
23	0.18	0.87	0.57	1.00	1.31	0.96	1.16	1.48	1.20
24	0.53	0.66	0.43	1.12	0.96	0.87	1.23	1.12	1.20
25	0.51	0.75	0.58	1.12	1.18	0.84	1.26	1.53	0.92
26	1.00	0.67	0.88	1.20	1.13	1.14	1.23	1.22	1.23
27	0.97	0.96	0.62	1.23	1.23	0.99	1.24	1.32	1.21
28	0.72	1.03	0.64	1.06	1.25	0.89	1.08	1.23	0.73
29	0.98	0.84	0.75	1.17	1.13	1.09	1.24	1.16	1.26
30	1.21	1.20	0.99	1.24	1.08	1.14	1.16	1.15	1.13
31	0.78	0.67	0.31	1.04	0.98	0.95	1.14	1.17	1.14
32	0.74	0.67	0.70	1.06	0.84	1.09	1.17	0.72	1.20
33	0.90	0.28	0.30	1.09	1.05	0.81	1.19	1.28	1.09

Appendix A: Continued



APPENDIX B

Appendix B: Raw data and boxplot of bulk density (BD) at each soil depth and sampling location in CR 1003.

# of transect	On (0-10 cm)	Center (0-10 cm)	Reference (0-10 cm)	On (10-20 cm)	Center (10-20 cm)	Reference (10-20 cm)	On (20-30 cm)	Center (20-30 cm)	Reference (20-30 cm)
1	0.79	0.59	0.45	0.92	0.82	0.58	0.89	0.81	0.65
2	0.70	0.60	0.55	0.74	0.74	0.68	0.86	0.76	0.73
3	0.71	0.67	0.24	0.85	0.75	0.46	0.82	0.77	0.62
4	0.63	0.53	0.38	0.70	0.67	0.48	0.67	0.75	0.49
5	0.59	0.20	0.54	0.70	0.45	0.56	0.75	0.51	0.59
6	0.53	0.41	0.29	0.59	0.60	0.57	0.63	0.65	0.69
7	0.89	0.92	0.72	1.17	1.09	0.78	1.21	1.19	1.03
8	0.34	0.37	0.35	0.85	0.61	0.55	0.97	0.93	0.65
9	1.01	0.78	0.54	1.30	1.11	1.01	1.37	1.21	1.02
10	0.95	0.92	0.64	0.96	1.31	0.79	1.31	1.32	0.91
11	0.63	0.64	0.81	1.33	1.00	1.13	1.23	1.07	1.19
12	0.79	0.93	0.65	1.07	1.16	0.86	0.96	1.06	1.08
13	0.69	0.67	0.88	1.15	0.63	0.94	0.99	0.83	0.97
14	1.06	1.08	0.81	1.22	1.35	0.62	1.19	1.36	1.09
15	0.66	0.81	0.72	0.72	0.84	1.01	0.84	0.69	1.20
16	0.88	0.74	1.06	1.01	0.55	1.15	1.13	0.96	1.19
17	1.10	0.46	0.75	1.01	0.60	1.05	1.18	0.95	1.03
18	1.10	0.66	0.78	1.20	0.88	0.77	0.99	0.99	1.13
19	0.53	1.02	1.29	1.02	1.12	1.45	1.18	1.17	1.43

Appendix B: Continued

# of transect	On (0-10 cm)	Center (0-10 cm)	Reference (0-10 cm)	On (10-20 cm)	Center (10-20 cm)	Reference (10-20 cm)	On (20-30 cm)	Center (20-30 cm)	Reference (20-30 cm)
20	1.14	1.12	0.91	1.36	1.20	1.28	1.23	1.19	1.27
21	0.95	0.41	0.77	1.25	0.98	1.17	1.20	1.04	1.09
22	1.14	0.84	1.05	1.11	1.08	1.29	1.19	1.08	1.12
23	1.08	0.95	0.81	1.37	1.15	1.06	1.30	1.30	1.08
24	0.54	0.58	0.71	1.06	0.64	1.02	1.16	0.75	1.19
25	0.81	0.78	0.95	0.98	0.98	1.25	0.90	1.01	1.13
26	1.06	0.83	1.01	1.31	1.05	1.15	1.30	1.07	1.17
27	0.82	0.41	0.43	1.25	0.52	0.68	1.25	0.59	0.79
28	0.87	0.53	0.89	1.16	1.20	1.17	1.08	1.21	1.15
29	1.06	0.77	0.88	1.13	1.11	0.87	1.08	1.12	1.00
30	0.88	0.78	0.54	0.84	1.07	0.98	0.87	1.13	0.98
31	1.02	0.90	0.55	1.19	1.14	0.90	1.23	1.12	1.10

Appendix B: Continued