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ARTICLE

Soil compaction from cut-to-length thinning operations in young redwood forests in northern California

Kyungrok Hwang, Han-Sup Han, Susan E. Marshall, and Deborah S. Page-Dumroese

Abstract: In northern California, United States, a cut-to-length (CTL) system was recently used for the first time to harvest young redwood (*Sequoia sempervirens* (Lamb. ex D. Don) Endl.) forests. Landowners and public agencies in this region have been concerned about the potential negative impacts of CTL on soils during wet-season harvest operations. To determine soil impacts, we measured changes in soil bulk density (BD) and hydraulic conductivity (HC) after CTL operations in May and August. Soil samples were collected at two locations (track and center) along forwarder trails and at a reference point at three soil depths (0–5, 10–15, and 20–25 cm), and HC samples were collected only at the 0–5 cm soil depth from the same sample points. We found a significant difference in BD between the reference point and track at 0–5 cm, which decreased as soil depth increased. There was a negative correlation between initial BD values and percent increase of BD, supporting the fact that the percent increase in BD was high at the soil surface (25%–30%), but BD did not exceed 1.13 $Mg \cdot m^{-3}$ at the 0–5 cm depth. However, our HC results were different from what we expected and were not as consistent as the BD results, as the HC data had much higher variability.

Key words: mechanized system, forwarding trails, slash, infiltration rate, bulk density.

Résumé : Dans le nord de la Californie, aux États-Unis, un système de récolte de billes de longueur préétablie (BLPE) a récemment été utilisé pour la première fois pour récolter les jeunes forêts de séquoia côtier (*Sequoia sempervirens* (Lamb. ex D. Don) Endl.). Les propriétaires et les organismes publics dans cette région étaient préoccupés par les impacts négatifs potentiels du système BLPE sur les sols lors de travaux de récolte réalisés durant la saison humide. Pour déterminer les impacts sur le sol, nous avons mesuré les changements de densité apparente (DA) et de conductivité hydraulique (CH) du sol après la récolte effectuée durant les mois de mai et août. Plusieurs séries de trois échantillons ont été prélevées : deux échantillons dans les sentiers de débardage (ornière et centre) et un troisième servant de point référence, à l'extérieur des sentiers, à trois profondeurs dans le sol (0–5, 10–15 et 20–25 cm). Aux points de référence, les échantillons utilisés pour mesurer la CH n'ont été prélevés qu'à 0–5 cm dans le sol. Nous avons trouvé une différence significative de DA entre les points de référence et les ornières à 0–5 cm qui diminuait avec la profondeur. Il y avait une corrélation négative entre les valeurs initiales de DA et le pourcentage d'augmentation de la DA, ce qui valide le fait que le pourcentage d'augmentation de la DA était élevé à la surface du sol (25–30 %), mais la DA n'a pas dépassé 1,13 $Mg \cdot m^{-3}$ à 0–5 cm de profondeur. Cependant, nos résultats de CH étaient différents de ceux qui étaient attendus car ils n'étaient pas aussi cohérents que la DA parce que les données de CH étaient beaucoup plus variables. [Traduit par la Rédaction]

Mots-clés : système mécanisé, sentiers de débardage, résidus de coupe, taux d'infiltration, densité apparente.

1. Introduction

Coastal redwood (*Sequoia sempervirens* (Lamb. ex D. Don) Endl.) forests extend from central and northern California to southern coastal Oregon in the United States and are associated with the fog belt and a sustainable moisture supply. Coastal redwoods have high-value wood, which has caused an increase in thinning operations within these forest types (Noss 1999). In addition, cut trees sprout vigorously and abundantly in a clump after thinning (Cole 1983). Because of the great size of old-growth redwood trees, loggers used to harvest trees by using manual felling methods. Over time, coastal redwood forests have transitioned from old-growth to younger stands (<25 years old) with high densities. These changes in stand dynamics have resulted in smaller trees that can be harvested using mechanized systems; however, sustainable harvest operations must also maintain site and soil productivity into the future. One metric of altered productivity from mechanized harvesting is a change in soil physical properties (e.g., soil compaction and hydraulic conductivity).

We found no studies that evaluate changes in soil physical properties associated with thinning operations in the coastal redwood forests. Altered soil physical properties result from trafficking, which pushes soil aggregates together to increase soil compaction (Wolkowski and Lowery 2008). Once this occurs, it affects both soil resilience and forest productivity. Compaction increases soil strength (Froehlich and McNabb 1984) and reduces air-filled porosity, resulting in less root growth (Froehlich et al. 1980). Reduced infiltration by soil compaction also leads to increased runoff and soil erosion, resulting in reduced nutrient availability and cycling by soil organisms, less topsoil for tree growth, and loss of surface organic matter (Lowery et al. 1996; Adams 1998).

The extent, amount, duration, and degree of soil impacts from harvesting depend on several factors such as soil texture (Heilman 1981; Pierce et al. 1983), moisture content (Coder 2000; Han et al.

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K. Hwang. School of Environmental and Forest Sciences, University of Washington, Seattle, WA 98195, USA.
H.-S. Han. Ecological Restoration Institute, Northern Arizona University, Flagstaff, AZ 86011, USA.
S.E. Marshall. Department of Forestry and Wildland Resources, Humboldt State University, Arcata, CA 95521, USA.
D.S. Page-Dumroese. USDA Forest Service Rocky Mountain Research Station, Moscow, ID 83843, USA.

Corresponding author: Kyungrok Hwang (email: kh2322@uw.edu).

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2006, 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 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 with fine-textured soils (e.g., silt and clay) (Williamson and Neilsen 2000). Also, when soil moisture is high, soils are more prone to the compaction forces of heavy equipment (Adams and Froehlich 1984). The use of cut-to-length (CTL) harvest systems has become more widespread. The CTL system is composed of a harvester and forwarder; as the harvester falls and processes the trees, slash 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 levels of moisture content, and there are models that 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 of the soil compaction occurred within 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 soils 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, United States, and concluded that CTL systems generated less soil compaction (27%–28%) than WT systems (34%–39%) at 7.5 cm soil depth on ashy silt loam soil. This is because CTL harvest systems generally impact less land area than WT systems. This is especially critical because most compaction occurs during skidding or forwarding operations. For example, a greater land area was impacted when using a skidder as compared with a forwarder system (Lanford and Stokes 1995).

The use of mechanized harvest operations in forestry has increased rapidly during the last three decades, and CTL harvesting has recently been introduced to northern California to harvest coastal redwoods. This system is particularly appropriate for use on coastal redwoods because it can be used to cut small- to medium-sized trees (diameter at breast height (DBH; breast height = 1.35 m) of 10–41 cm) (Kellogg et al. 1992) and it simplifies operations by eliminating the use of a loader (Adebayo et al. 2007). It is therefore critical to understand the impact of CTL logging on soils in coastal redwood forests to maintain site and soil productivity. We designed this study to determine CTL logging impacts on soil in two harvest units. The goals of our study were to (*i*) determine the degree of soil compaction after CTL harvesting on soils with high soil moisture content and (*ii*) review the factors that affect soil compaction.

2. Materials and methods

2.1. Site description

The commercial thinning operations were performed in two harvest units (Fig. 1). Harvesting occurred in the Crannell tract of the 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). The CR 1200 stand was harvested from January to April, and the CR 1003 stand was harvested from June to August, using CTL systems. We also analyzed the soil characteristics by collecting additional soil samples right before each operation (Table 1). The soil at CR 1200 was primarily silt loam with a bit of sandy loam and included 12%–14% organic matter, whereas CR 1003 was mostly covered by loam with some silt loam and included 12%–17% organic matter. These two stands were originally selected to provide a range of soil moistures, but CR 1200 and CR 1003 had mean soil moisture contents of 53% and 45%, respectively, during harvesting, which was not a large enough difference for comparison. After operation, the moisture contents were reduced by 49% and 34% in CR 1200 and CR 1003, respectively. The CR 1200 unit was 10.1 ha in size, with a 1.2 ha Watercourse and Lake Protection Zone (WLPZ) at an elevation of 126 m, and had a relatively flat ground slope (approximately 0%). Detailed information on stand characteristics is displayed in Table 2. Redwood was the most dominant species at CR 1200, followed by red alder (*Alnus rubra* Bong.), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), and Sitka spruce (*Picea sitchensis* (Bong.) Carrière). The CR 1003 unit was 12.1 ha in size and had an elevation of 188 m, with slopes ranging from 0% to 27%. The site was dominated by redwood, as well as red alder, Sitka spruce, and Douglas-fir. The precipitation during harvesting at CR 1200 was 896 mm, whereas the precipitation during harvesting at CR 1003 was only 17 mm.

On unit CR 1200, the redwood forests were harvested using a Ponsse Bear harvester (Ponsse, Vieremä, Finland) with a Ponsse H8 harvester head (mass 24 500 kg) to fell, delimb, and buck the trees. On unit CR 1003, harvesting was done using a Ponsse Ergo harvester with a Ponsse H7 harvester head (mass 21 500 kg). Each unit had a different equipment operator, with the operator at CR 1200 having more than 20 years of experience and the operator at CR 1003 having only 5 years of experience. The forwarding operation for each unit was performed by the same machine (Ponsse Buffalo) with the same driver. The mass of the forwarder was 14 150 kg, and it had a maximum payload of 14 000 kg. The objectives of thinning were to (*i*) remove dead trees, (*ii*) increase tree spacing, and (*iii*) reduce fuel continuity. The harvest operators were directed to avoid cutting trees with DBH > 60 cm, maintain at least 60% canopy closure, and retain the healthiest dominant and codominant trees. The harvester operators were also directed to use the logging slash to buffer the soil from soil compaction during harvest operations.

2.2. Data collection

We collected an initial set of samples to characterize soil physical properties such as soil texture and moisture content before harvesting. Soil particle size distribution was determined using a hydrometer, and soil organic matter was quantified by conducting loss on ignition (LOI) at 375 °C for 16 h (Liu and Evett 1984).

After harvesting, we collected measurements of soil bulk density (BD) and hydraulic conductivity (HC). Soil samples were collected with a slide hammer corer (AMS Inc., American Falls, Idaho, USA; volume 90.59 cm^3). Samples were collected from the depths of 0–5, 10–15, and 20–25 cm in the mineral soil. Before collecting soil cores, we removed the logging residues and forest floor to locate the top of the mineral soil. BD cores were collected on a 3.6 m transect across the forwarder trail at 150 m intervals. Soil cores were collected from three locations: in one of the wheel tracks, at centerline, and 2 m away from outside edge of the track (reference point) (Fig. 2). We assumed that at the reference point there were no passes from either harvester or forwarder, indicating no soil disturbance. A total of 33 transects with 297 samples were collected in CR 1200, and 31 transects with 279 samples were collected in CR 1003. Cores were placed in plastic bags for transport from the field to the laboratory. In the laboratory, soil samples were weighed, oven-dried at 105 °C for 24 h, and reweighed to the nearest 0.01 g.

In addition to the BD cores, a mini-disk infiltrometer (Decagon Devices, Pullman, Wash., USA) with a diameter of 3.1 cm was used to measure the infiltration, with the suction rate adjusted to 2 cm. The field data were collected adjacent to each BD sample point. Infiltration measurement was only performed on the mineral soil surface. We recorded water volume every 30 s for a total of 300 s.

Fig. 1. Map of the study sites and the forwarding trails used by cut-to-length (CTL) systems. WLPZ, Watercourse and Lake Protection Zone. Map generated using ArcGIS software. [Color online.]

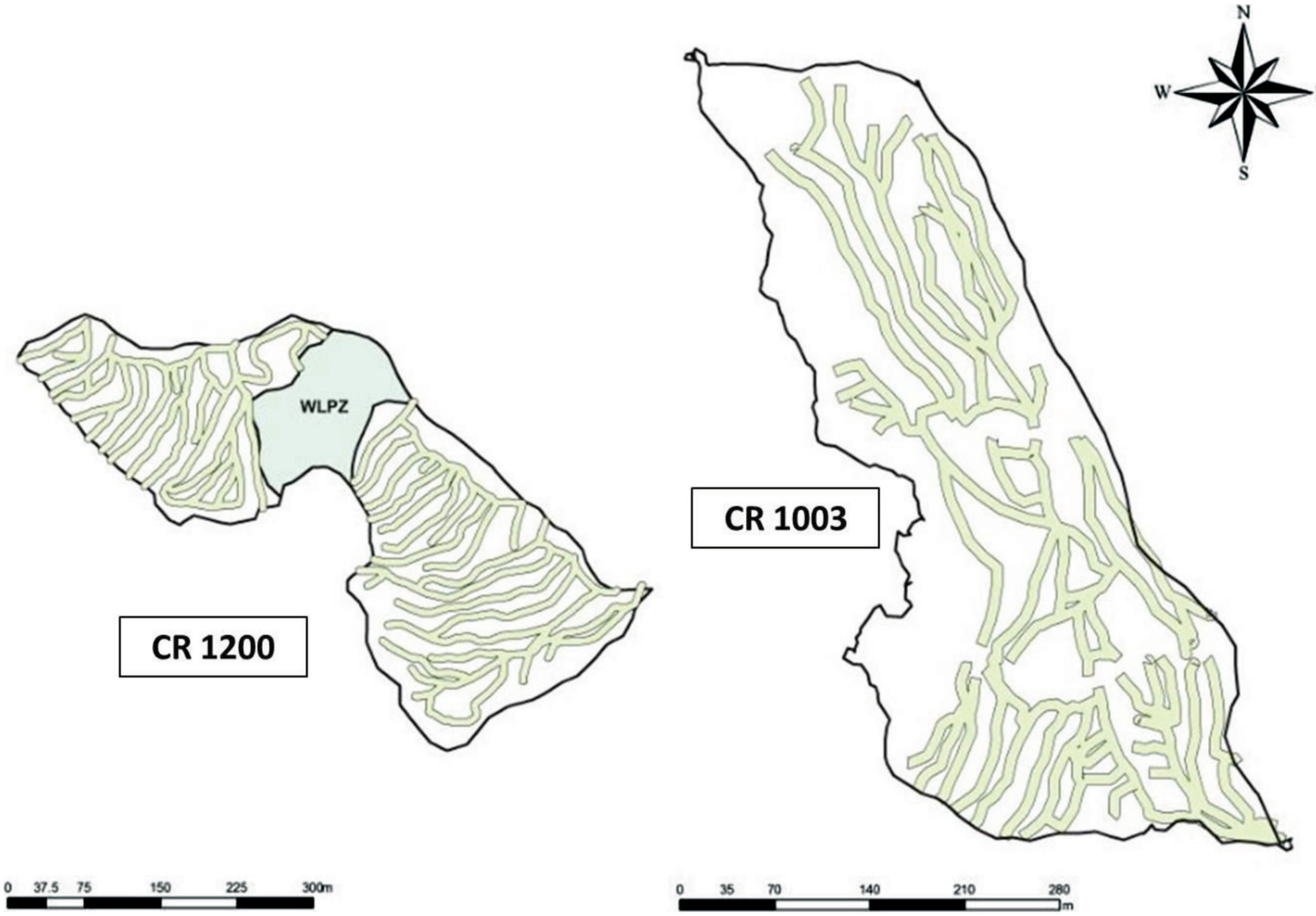


Table 1. Soil particle size distribution, organic matter, and gravimetric moisture content within each harvest unit in northern California ($n = 18$).

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

Note: All values are means.

Table 2. Stand characteristics and climatic data before thinning.

Unit	Area (ha)	Temperature (°C)	DBH (cm)	Height (m)	Trees per hectare
CR 1200	10.1	7	20	19	2390
CR 1003	12.1	16	21	19	1970

Note: All values except areas are means. Trees per hectare only included trees with diameter at breast height (DBH; breast height = 1.35 cm) of 5 cm or greater.

Based on the mini-disk data, we calculated HC and the cumulative infiltration rate over time using the following equations. 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, t is time (in seconds), and C_1 (in metres per second) and C_2 (in metres per square-root second) are parameters. C_1 is related to HC, and C_2 is the soil sorptivity. The HC of the soil (k) is computed from

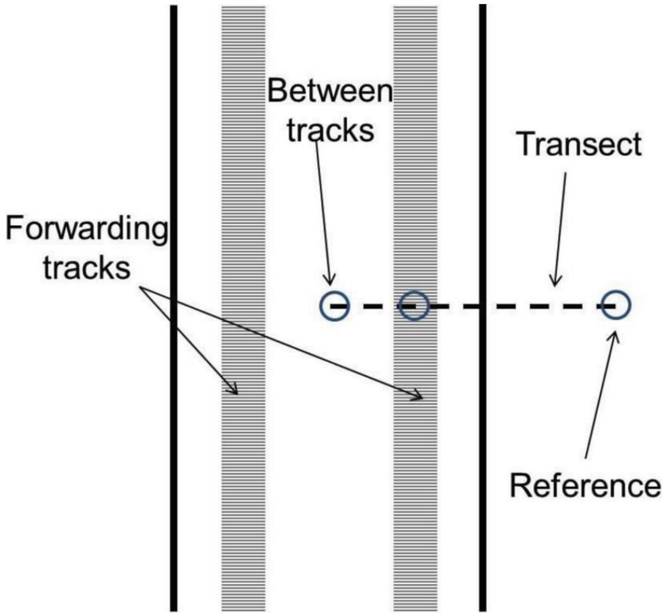
$$k = \frac{C_1}{A} \tag{2}$$

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

where C_1 is the coefficient of the cumulative infiltration curve versus $\sqrt{t}$, A is a value relating the van Genuchten parameters for a given soil type relative to the suction rate, n and α are the soil van Genuchten parameters, and r_0 and h_0 are the disk radius and suction rate at the disk surface, respectively. We used the van Genuchten parameters developed by Carsel and Parrish (1988) for the silt loam and loam soil in the study area.

After harvesting, we collected forwarder trail width and length data by walking each trail with a Global Positioning System (GPS) unit (Garmin Schaffhausen, Switzerland). The width of each trail was measured every 20 m to determine mean trail width. Width and total length of the trail were used to determine trail coverage within each harvest unit. We mapped each trail from the log

Fig. 2. A diagram showing locations of the sample points (track, center, and reference) along the forwarding trails. Blue circles are the sample points. [Color online.]



landing using ArcGIS 10.4.1 (Esri, Redlands, Calif., USA) to determine the number of transects needed for soil sampling. This information was used to determine the relationship between the number of machine passes and BD and was used instead of counting the number of machine passes manually; as the distance from the landing site increases, the number of machine passes decreases (Han et al. 2009).

2.3. Logging residue determination and statistical analyses

Slash amounts were estimated by the downed woody debris survey method using the Brown transect method (Brown 1974) and allometric equations (Jenkins et al. 2004; Kizha and Han 2015). All logging residues were placed on the trails as harvesting progressed, and we assumed that 90% of the logging residues from the thinning operation would be concentrated on the trails based on visual observation. Our estimates were on a green-ton basis, and we assumed that logging residues had approximately 50% moisture content and converted from green ton to a mass in kilograms.

Data were analyzed using SPSS 24 (IBM, Armonk, N.Y., USA) and R (R Development Core Team 2008). We tested for normality using the Shapiro–Wilk normality test and homogeneity of variance tests before comparing sampling locations. The analysis of variance (ANOVA) test was performed to identify the interaction of BD in each unit, sampling location, and soil depth, and we compared the level of soil compaction among the three sampling locations (track, center, and reference) at each depth using the Kruskal–Wallis test and Holm's method for multiple comparisons. Likewise, the Kruskal–Wallis test was used to compare the HC among sampling locations in each unit. All analyses were performed at an alpha level (α) of 0.05.

3. Results

3.1. BD comparison

As the interaction of depth × location did not have a significant effect on BD, we herein explore the effects of depth and sampling location separately (Table 3). For all sample points (track, center, and reference), we found the lowest BD in the surface mineral soil (0–5 cm depth). In unit CR 1200, the mean BDs of the reference points were 0.70, 0.98, and 1.09 $\mathrm{Mg \cdot m^{-3}}$ at soil depths of 0–5, 10–15, and 20–25 cm, respectively (Table 4). At both the 0–5 and 10–15 cm depths, there were significant differences between the track and reference points, but there were no significant differences between the track and center points at these same depths. At the 20–25 cm depth, there was no significant difference among the three locations. In unit CR 1003, the mean BDs were 0.71, 0.91, and 0.99 $\mathrm{Mg \cdot m^{-3}}$ for the reference points at depths of 0–5, 10–15, and 20–25 cm, respectively. At this site, the track had significantly higher BD than both the center and reference points at the 0–5 cm depth, and there was no significant difference between the center and reference BDs at the 0–5 cm depth. In addition, there were no significant differences between track and center at the 10–15 and 20–25 cm soil depths. The largest increase of BD was detected in the surface soil: 25.5% in CR 1200 and 30% in CR 1003 (Fig. 3). The increase in BD decreased with soil depth.

Table 3. Two-way analysis of variance (ANOVA) from CR 1200 and CR 1003 showing the effects of depth and location and their interaction (depth × location) on bulk density.

	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

Note: ***, $p \leq 0.001$. df, degrees of freedom.

Table 4. Mean (± standard deviation) bulk density ($\mathrm{Mg \cdot m^{-3}}$) collected from soil samples at the track, center, and reference points.

Unit	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 same letters indicate no significant difference at each soil depth within each unit. *n*, number of transects.

3.2. HC comparison

At the reference point in unit CR 1200, HC was 1.29 $\mathrm{cm \cdot h^{-1}}$, whereas in unit CR 1003, HC was only 0.38 $\mathrm{cm \cdot h^{-1}}$, but both had relatively high standard deviations (Table 5). In CR 1200, HC in the forwarding track was lower than that of the reference point, but the differences were not significant ($p = 0.6439$). In CR 1003, however, HC in the track was significantly higher than that of the reference point. In both units, there were no significant differences in HC between the track and center.

4. Discussion

4.1. BD

We detected differences in BD 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 when using CTL systems on ashy loamy soil in the Inland Northwest, showing that a significant difference was detected in the surface mineral soil, but there were no detectable differences as the soil depth increased. In a study on sandy loam soils, McNeel and Ballard (1992) reported that mean preharvest BDs were 0.71, 0.82, and 0.87 $\mathrm{Mg \cdot m^{-3}}$ at soil depths of 10, 20, and 30 cm, respectively, which increased to 0.85, 0.92, and 0.99 $\mathrm{Mg \cdot m^{-3}}$, respectively, with intense traffic by using a CTL system in a Douglas-fir plantation. McDonald and Seixas (1997) found that in the mineral soil (0–5 cm depth), BD was significantly greater regardless of slash amount, but there was no significant increase in BD at the 15–20 cm soil depth on loamy sand with no vegetative cover. They also noted

Fig. 3. Percent increase of bulk density (BD) on the track after harvesting at each soil depth (0–5, 10–15, and 20–25 cm) in each unit (CR 1200 and CR 1003). [Color online.]

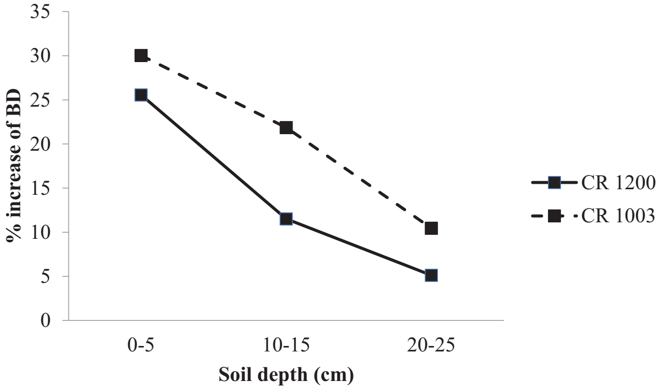


Table 5. Mean values (± standard deviation) for hydraulic conductivity (cm·h⁻¹) collected from soil samples at the track, center, and reference points at 0–5 cm soil depth.

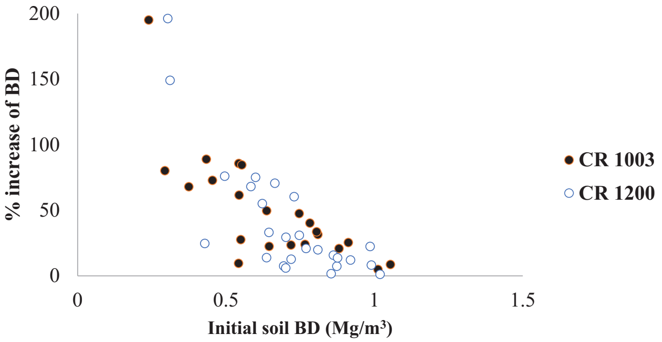
Unit	*n*	Track	Center	Reference	*p* value
CR 1200	33	1.23 ± 1.45^{a}	1.95 ± 2.78^{a}	1.29 ± 1.47^{a}	0.6439
CR 1003	31	1.61 ± 2.08^{a}	0.93 ± 1.52^{ab}	0.38 ± 0.54^{b}	0.0396

Note: The same letters indicate no significant difference within each unit. *n*, number of transects.

that the percent increase of BD was highest at the 0–5 cm soil depth and decreased with soil depth. In our study, there was a large percent increase of BD in both units (25% for CR 1200 and 30% for CR 1003) at the 0–5 cm soil depth. Han et al. (2009) showed that when using a CTL system on ashy loamy soil, an increase in BD of almost 30% was observed at 7.5 cm soil depth. In addition, pretreatment soil moisture contents at our sites were higher than those of other studies, ranging from 49% to 58%. Han et al. (2009) showed that soil moisture is a significant factor affecting the soil compaction in a CTL system by differentiating the levels of moisture content.

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 (Fig. 4), similar to the findings of Page-Dumroese et al. (2006). Ampoorter et al. (2012) also suggested that if soil BD before harvesting is higher, then there may be only a slight increase in BD. 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, implying that machine passes had little effect on soils that were already compacted. In addition, Han et al. (2009) developed models that enabled them to predict changes in soil BD with 25%–30% moisture content, which provides one method for determining soil impacts before logging operations begin. In this study, we tried to find the effect of machine passes using the distance to the landing, but there were so many factors, including operating technique, site and stand condition, volume concentration, and distribution, that distance alone could not capture the relationship between these two variables.

Fig. 4. The relationship between initial soil bulk density (BD) and percent increase of BD. [Color online.]



4.2. 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 the three locations at CR 1200, and unexpectedly, in-track HC was significantly higher than off-track HC at CR 1003. Greacen and Sands (1980) reported that compaction may not necessarily alter the volume of micropores, thus the unsaturated HC in our data may be unaffected or even increased. Although we found significant changes in BD between the compacted and uncompacted areas, the porosities were likely still high, showing high HC despite machine trafficking. Rose (1966) suggested that soil HC is strongly affected by pore geometry complexity and water content, so it is recommended to conduct soil porosity analysis for more details by separating it into macro- and microporosities.

Researchers have been interested in how fast soils recover after increased compaction. This can be a complex question and depends on the degree of compaction, content of soil organic matter, presence of a freeze–thaw cycle, shrink–swell capacity, root growth, and movement of belowground fauna (Vanderheyden 1981; Froehlich and McNabb 1984). Page-Dumroese et al. (2006) indicated that on coarse-textured soils, compaction recovery can be relatively quick (within 5 years), but on fine-textured soil, recovery may take decades to return to predisturbance levels. Previous logging on our site occurred 30 years ago, and we could detect a few old skid trails before the current logging operation. Therefore, we cannot say if compaction recovery had occurred or if the previous trails were masked by the increasing forest floor. Although fast recovery can occur from deep soil profile freezing (Mace 1971), the northern California coastal redwood zone is more prone to heavy rains and usually has soil temperatures above 0 °C. This indicates that any increases in HC from the harvest may not have been increased. However, we found no data about earthworm movement or root growth in this area, which may have also mitigated compaction or increased 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 have large standard deviations at all sampling locations. 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 we collected an insufficient sample size. Nielsen et al. (1973) suggested that the true variation in water movement that exists from place to place in any area should be examined with a large number of samples. We estimated HC from 31–33 transects within a 10–12 ha area, making it difficult to be sure that our HC samples fully explain each sample location (track, center, and reference) and site variability.

4.3. 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, 2009). In our study, the equipment operator created large amounts of logging residues to prevent soil disturbance (Table 6). Usually, logging residues are weighed to determine the total amount

Table 6. Amount of slash covering the forwarding trails.

Unit	Prethinning (kg·m^{-2})	Postthinning (kg·m^{-2})	Total (kg·m^{-2})
CR 1200	2.3	29.8	32.1
CR 1003	8.2	17.1	25.3

Table 7. Mean trail width, trail area, and expected compacted area from the cut-to-length (CTL) system.

		Trail width		Trail area		Compacted area	
Unit	Total 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: Trail width is composed of the tracks and center area.

remaining (Han et al. 2006); however, we had sawlogs and a large amount of branches, twigs, and stems that we could not adequately weigh. Therefore, we used two methods (allometric equations and Brown's method) to determine how much logging residue was present. On ashy loamy soil, Han et al. (2009) noted that the degree of soil compaction when using CTL was severe when the soil was exposed as compared with 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; they noted a 16% increase in BD on sites with heavy logging residues (18.6 kg·m^{-2}), a 21% increase in BD on sites with light logging residues (9.2 kg·m^{-2}), and a 25% increase in BD 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 amounts of logging residues. Plentiful logging residues on wet soils could have minimized the amount of soil compaction that we found. McDonald and Seixas (1997) also confirmed that logging residues had a more significant effect on wet soil than dry conditions when using a 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 potentially reduced equipment impacts on the mineral soil even though our soils were relatively wet.

The amount of organic matter within the mineral soil may also affect the amount of soil compaction by equipment (Froehlich and McNabb 1984; Dexter 2004). Ares et al. (2005) suggested that large areas of forest soils in the Pacific Northwest are covered with high organic carbon content with relatively low BD, which distinctly minimizes the impacts on forest site productivity. Coastal redwood sites in our study had a large amount of soil organic matter from understory inputs, a large amount of overstory 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 machine passes. They also reported that the BDs in wet conditions were lower than those in dry conditions as machine passes increased (0.9–1.0 Mg·m^{-3} versus 1.2–1.4 Mg·m^{-3}), suggesting that the soils in areas of low rainfall with lower contents of organic matter had the highest BDs, whereas soils in areas of high rainfall with higher contents of organic matter had the lowest BDs.

We could not measure the machine characteristics in the fields (e.g., ground pressure or equipment speed); however, we noted that bogie tracks were used with the harvester and forwarder. Equipment with bogie tracks is used to disperse the load to a greater area (i.e., to not concentrate it on a small area), which can be effective for minimizing ground pressure on soil compared with using conventional wheels (Bygdén et al. 2003; 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 with wheel tracks (Bygdén et al. 2003). In addition, as previously mentioned, there was a logging operation 30 years ago on our site, and the soil might be relatively resistant to further compaction in each unit. Ampoorter et al. (2012) found that once the soil was compacted, any soil would be relatively tolerant to further compaction because of an increase in micropores and a decrease in macropores.

4.4. The extent of compaction on forwarding trails

Compared with WT operations, we could detect the forwarding trails in CTL operations because of the relative repetitive movement. The center points in unit CR 1200 were compacted, but we did not find similar impacts in unit CR 1003. This is due to equipment trafficking across the centerline of the trail. 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 dissimilarly over the forwarding trails (Table 7). McNeel and Ballard (1992) calculated that the forwarding trails accounted for 19.7% of the area, and Lanford and Stokes (1995) reported that 38% of the area was disturbed when using a CTL system. Han et al. (2009) suggested a different calculation that distinguishes between the centerline and the track. They reported that approximately 19%–20% of total harvesting unit was covered by trails from the CTL system; however, the actual compacted area was reduced by up to 10%.

4.5. Acceptable levels of 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 0.70 and 0.71 g·cm^{-3} to 0.83 and 0.84 g·cm^{-3} in CR 1200 and CR 1003, respectively. Several studies have shown that increasing BD can limit that the root growth (Daddow and Warrington 1983; Pierce et al. 1983). Pierce et al. (1983) suggested that the 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 United States Department of Agriculture (USDA) Forest Service has used a threshold of a 15% increase in BD to ensure long-term soil productivity in the 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 increase in BD at some locations would exceed the threshold of 15%. 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 by more than 10%, there will be a decrease in root growth for residual young ponderosa pine (*Pinus ponderosa* Douglas ex P. Lawson & C. Lawson), but this change may not be great enough to limit ground-based logging. Compaction caused by a vibratory soil compactor in plantations of ponderosa pine aged 3–8 years old 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, as compaction is 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 causing an increase in BD.

4.6. Best management practices (BMPs) for CTL operations

Powers et al. (1998) suggested that estimations of soil quality thresholds for a wide range of soils are difficult and that forest soils are susceptible to disturbance (e.g., compaction and forest floor removal). Furthermore, it is difficult to estimate postdisturbance recovery time for individual soils. Many studies have examined the impacts of harvest operations on soil properties and subsequent stand growth (Ares et al. 2005; Labelle and Jaeger 2011; Achat et al. 2015) and, in general, WT harvest operations remove forest residues, resulting in an export of soil nutrients such as carbon, nitrogen, phosphorus, and potassium, leading to declines in residual tree growth (Palviainen and Finér 2012; Naghdi et al. 2016).

Unlike WT systems, CTL systems generally require less area to transport logs and result in fewer impacts on soil physical properties. CTL systems leave a greater amount of forest residues onsite to act as a buffer against rutting, compaction, and the mixing of forest floor and topsoil (Froehlich et al. 1986; Han et al. 2009; Labelle and Jaeger 2011; Missanjo and Kamanga-Thole 2014).

There are few soil studies on which to base BMPs for CTL harvest operations in young-growth redwood stands. However, performing harvest operations at times when the soil is dry can limit the severity and extent of soil compaction to ensure adequate growth of the residual redwood stands. Retaining forest residues can also maintain soil quality for residual tress or the next rotation (Ghaffariyan and Apolit 2015). In redwood stands, O'Hara et al. (2010) noted that because decomposition occurs quickly, it should be relatively easy to manage forest residues while minimizing fire danger. Restoration of these stands by silvicultural manipulation is key to the acquisition of old-growth properties (Keyes and Teraoka 2014); therefore, understanding the impacts of CTL and WT harvest operations on soil properties will also help achieve restoration targets.

5. Conclusions

This is the first CTL study on coastal redwoods in northern California to assess changes in BD and HC on soils with high moisture content (49%–58%). The actual values of BD on the tracks were low; however, in both units, there was a high percent increase in BD (25%–30%) on the tracks. HC data showed inconsistent results because of high spatial variability, so we recommend analyzing soil porosities for a more detailed analysis by separating into macro- and microporosities with a greater number of samples. When we separated the forwarding trails (disturbed versus undisturbed area) and considered only compacted area, the overall compacted area was reduced. Thus, it is recommended that operators move carefully by using the same trails in the CTL system when they drive and avoid crossing the centerline of the forwarding trails. In northern California, a CTL system would not detrimentally affect the root growth based on actual values of BD; however, the percent increases of BD were beyond the standards set by the USDA Forest Service. The impact depends on site factors such as species and soil texture, so it is recommended that future studies examine the long-term impacts from the CTL system on forest growth.

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