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Mechanized fuel treatment effects on soil compaction in Sierra Nevada mixed-conifer stands

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Abstract

The immediate need to treat forest fuels is often justified as a need to reduce potential fire behavior as well as improve or maintain forest health. Millions of hectares are at risk of unusually severe fires in the United States, and fuel treatments are being prescribed at unprecedented scales. In many cases, mechanical treatments with heavy equipment are the most efficient or economical method to reduce fuels. Despite the large-scale emphasis on both mechanical fuel modifications and forest health, few studies of fuel treatment effects have examined impacts to forest soils. We evaluated fuel treatment effects on soil compaction in a managed Sierra Nevada mixed-conifer forest using a fully replicated study design with three treatments: Thin, Thin + Burn, and an untreated Control. To examine impacts of mastication equipment that travels throughout a stand to reduce fuels, soil sampling was stratified to address effects at the scale of the treatment unit, the skid trail network, and the non-skid trail area. At all scales, the Thin and Thin + Burn did not increase soil bulk density compared to the Control. At the treatment unit level, soil strength was increased in the Thin + Burn relative to Control, but this was attributed to increased strength in skid trails rather than in the non-skid portion of the stand. The compacting forces of the masticator were buffered by the debris bed it created, and no significant compaction due to mastication was observed away from skid trails. Soil strength appeared to be a more sensitive measure of compaction, although a very weak relationship was observed between soil bulk density and soil strength. Despite frequent stand entries prior to these fuel treatments, the cumulative extent of detrimental compaction was not increased as a result of the Thin and Thin + Burn treatments. Mean soil strength in skid trails was consistently greater than in non-skid trail areas to a depth of nearly 60 cm. Measures to avoid the creation of new skid trails will help curtail increased soil compaction in managed forest stands, and particularly in fuel treatment areas that may require repeated entries to remain effective.

Keywords: Fuel treatment; Mastication; Soil compaction

1. Introduction

Many dry forests in the United States (US) are currently managed to reduce fire risk by treating hazardous fuels. Federal land management policies emphasize the need to meet fuel reduction objectives by using mechanical, chemical, biological, or manual techniques, as well as prescribed fire (USDA-USDI, 2000; HFRA, 2003). While fuelbreaks are commonly constructed to reduce both fuels and wildland fire severity (Agee et al., 2000), often the objectives of forest fuel management also include the need to improve or restore forest health (Tiedemann et al., 2000; Carroll et al., 2004).

Many research studies that examine fuel treatments have focused primarily on the effects to fuels or fire behavior (e.g., Stephens, 1998; Carey and Schumann, 2003; Stephens and Moghaddas, 2005b). Until recently, relatively few fuel treatment studies have focused on other ecosystem components and processes, particularly in forest soils. Johnston and Crossley (2002) advocate that soil biological components should play a greater role in forest ecosystem management. Indeed, recent research has reported on forest thinning and prescribed burning fuel treatment effects on soil respiration (Ma et al., 2004; Kobziar and Stephens, 2006), lethal soil temperatures (Busse et al., 2005), leaf litter fauna (Apigian et al., 2006), and coarse woody debris (Stephens and Moghaddas, 2005a). Grigal (2000) emphasized that changes to soil physical properties as a result of forest management are of paramount importance to site productivity. Although fuel

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treatments often include widespread mechanical removals or on-site mastication of large amounts of non-merchantable material, relatively few studies have examined the effects of these intensive fuel treatments on soil compaction (Gundale et al., 2005; Hatchett et al., 2006; Moghaddas and Stephens, 2007).

A large body of literature describes the effects of forest thinning and other silvicultural treatments on soil compaction (Froehlich, 1974; McColl and Powers, 1984; Alexander and Poff, 1985; Ballard, 2000; Miller et al., 2004). Many of these studies summarize impacts that result from a single harvest entry. In the Western US, however, many stands that are being considered for fuel treatments have a long history of both extensive (e.g., number of stand entries) and intensive (e.g., site preparation, planting) timber management. Silvicultural practices in the Sierra Nevada have changed drastically from the 1850s to the present (Helms and Tappeiner, 1996), and many stands have been entered repeatedly during this time period. While forest stands are dynamic and resilient, over time, multiple entries can have cumulative impacts on forest ecosystems.

The objectives of our study were to examine the effects of mechanical fuel treatments on soil compaction in managed stands of the Sierra Nevada. The study site reflects a management history common throughout the region: pre-1900 logging with oxen, railroad logging in the early 1900s, heavy selective cuttings from 1960 to 1970, and single-tree and group selection harvests beginning in the mid 1980s (Stephens and Moghaddas, 2005b). Legacy effects from these activities are reflected in the stand structure, species composition, and transportation network used to access the stands. In particular, skid trail systems can greatly affect physical properties of the underlying mineral soil. In this paper, we report fuel treatment impacts on soil compaction across overall stands, within skid trails, and within the non-skid trail portions of the stands.

2. Materials and methods

2.1. Study site

Treatment units were located on the western slopes of the central Sierra Nevada at the University of California Blodgett Forest Research Station (38°54′N, 120°39′W) near Georgetown, California. Elevation ranges from 1100 to 1410 m. Total annual precipitation averages about 160 cm, falling mostly from October to early May. Mean monthly air temperature ranges from 4 °C in December and January to 21 °C in July and August (Blodgett Forest Research Station, 2007). Vegetation consists of mixed-conifer forest comprised of sugar pine (*Pinus lambertiana* Dougl.), ponderosa pine (*Pinus ponderosa* Laws), white fir (*Abies concolor* (Gord. and Glend.) Lindl.), incense-cedar (*Calocedrus decurrens* (Torr.) Florin), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), California black oak (*Quercus kelloggii* Newb.), tan oak (*Lithocarpus densiflorus* (Hook. and Arn.) Rehder), bush chinkapin (*Chrysolepis sempervirens* (Kell.) Hjelmg.), and Pacific madrone (*Arbutus menziesii* Pursh) (Stephens and Collins, 2004). The mineral soils are underlain by Mesozoic granitic material and are predominantly classified as the Holland and Musick series (fine-loamy, mixed, semiactive, mesic Ultic Haploxeralfs) (Olson and Helms, 1996). Table 1 displays mean soil characteristics of the upper 15 cm of mineral soil in each treatment type before and after treatment implementation. Treatment effects on soil chemistry were reported by Moghaddas and Stephens (2007).

2.2. Experimental treatments

This research was conducted at one of 13 study sites implementing the national Fire and Fire Surrogates Study (FFS). Treatments at all sites were designed to modify stand structure such that, following treatment, 80% of the dominant and co-dominant trees would survive a wildfire modeled under 80th percentile weather conditions (Weatherspoon and Skinner, 2002). A second objective was to create a stand structure that maintained or restored forest characteristics and processes such as snag and coarse woody debris recruitment, diversity of floral and faunal species, and seedling establishment. The forest floor and soils component was designed to determine the consequences of the fuel treatments on key aspects of forest floor and soil structure, function, biogeochemistry, and biodiversity (Weatherspoon and McIver, 2000). To meet these objectives at the Blodgett study site, three replicates each of four treatments including no treatment (Control), prescribed fire (Burn), mechanical treatment (Thin) and mechanical treatment followed by prescribed fire (Thin + Burn) were randomly assigned to 12 treatment units. The treatment units ranged from 14 to 29 ha, and data collection was restricted to a 10-ha core area in the center of each unit. As there were no mechanical operations in the burn

Table 1
Surface soil and stand characteristics before and after implementation of fuel treatments (average ± S.E.)

Soil property	Control	Thin	Thin + Burn
Surface texture	Sandy loam	Sandy loam	Sandy loam
Sand (%)	67 (2)	61 (1)	57 (5)
Silt (%)	24 (1)	27 (0)	29 (3)
Clay (%)	10 (1)	12 (0)	13 (2)
Forest floor depth (cm)			
Pre-treatment	6.6 (1.0)	5.7 (0.5)	6.3 (0.6)
Post-treatment	5.6 (0.4)	5.0 (0.6)	1.1 (0.1)
Mineral soil total C (g kg^{-1})			
Pre-treatment	50.63 (2.60)	53.77 (1.54)	62.18 (11.81)
Post-treatment	52.36 (3.21)	52.17 (2.43)	57.39 (6.61)
Exposed bare soil (%)			
Pre-treatment	5 (2)	8 (5)	3 (0)
Post-treatment	4 (2)	8 (1)	54 (9)
Trees (number ha^{-1})			
Pre-treatment	1101 (67)	972 (226)	823 (187)
Post-treatment	1110 (84)	429 (140)	239 (21)
Basal area (m^2 ha^{-1})			
Pre-treatment	55.1 (3.1)	51.9 (2.0)	55.1 (1.5)
Post-treatment	56.4 (3.0)	40.9 (0.8)	39.3 (2.5)

units, this paper does not address soil compaction effects caused by the burn treatment.

Control units received no treatment during the study period (2000–2005). Thin units were treated in two stages—commercial harvest followed by mastication. In 2001, stands were heavily thinned from below (Graham et al., 1999) to maximize crown spacing, retain 28–34 m^2 ha^{-1} of basal area, and produce an even mix of residual conifer species. Trees were felled, bucked and delimbed using a chainsaw, and boles were moved to landings with a rubber tired grapple skidder (528 Skidder, Caterpillar). Following the harvest, approximately 90% of understory trees between 2 and 25 cm diameter at breast height were masticated in place using a rotary disc brushcutter (Model 52 Series II QF Brushcutter, Pro Mac Manufacturing Ltd.) mounted to a track-laying excavator (John Deere 490E, Deere and Company). The brushcutter disc measured 1.32 m in diameter, and was mounted directly to the excavator boom without modification. The resulting masticated material was predominantly 0.6–8 cm in diameter and 0.1–0.3 m in length. This material was not removed from the experimental units. The remaining unmasticated understory trees were left in scattered clumps 0.04–0.20 ha in size. The operating weight of the masticator was approximately 12,100 kg, with an average ground pressure of 31 kPa (4.5 psi). Average mastication productivity was 0.25 ha h^{-1}. The Thin + Burn treatments first underwent the same treatment as the Thin units. In addition, they were prescribed burned using a backing fire in the fall of 2002. All treatments were fully described by Stephens and Moghaddas (2005a). Table 1 displays mean stand characteristics in each treatment category before and after treatment implementation. Treatment effects on stand structure, fuel loads, and potential fire behavior and severity were reported by Stephens and Moghaddas (2005b).

2.3. Soil sampling and processing

Pre-treatment soil sampling occurred from late May to August 2001. Post-treatment sampling occurred from June to August 2003. During each sampling period, mineral soil was collected from twenty 0.04-ha plots within each of the 9 treatment units (180 plots total). Six subplots were established at each plot for a total of 1080 subplots across the 9 treatment units. Each subplot was categorized as occurring in a skid trail or outside of a skid trail. Skid trails were identified based on visual indications of past equipment use, such as a water-barred equipment trail, a skid trail bed with cut and fill slope, a trail wide enough for a skidder that is clear of vegetation (except shrubs or young trees), with skinned or cat-faced trees along the edges of and facing the trail, and rutting in long, linear depressions resembling equipment tracks. At each subplot, a mineral soil core sample was collected from the 0 to 15 cm depth. The six subsamples from each plot were pooled into two categories: skid trail samples or non-skid trail samples. Soil bulk density was determined based on the total mass and volume of each sample. A subsample was dried to constant weight at 105 °C to correct for moisture. Soil strength was measured adjacent to each soil core using a recording cone penetrometer (Rimik CP20, Agridry Rimik Pty Ltd.). The six penetrometer readings at each plot were similarly grouped into skid trail and non-skid trail measurements.

2.4. Soil porosity and detrimental compaction

While this study was conducted on lands owned and managed by the University of California, much of the adjacent land ownership is managed by the US Forest Service (USFS). The USFS developed a Regional compaction threshold as guidance in determining levels that are detrimental to soil productivity. For the Pacific Southwest Region encompassing the study area, the guidance states, ‘‘Soil porosity should be at least 90% of total porosity found under natural conditions’’ (USDA Forest Service, 1995). According to this guidance, changes in soil porosity are to be determined based on a threshold soil bulk density, using the following formula:

$$\mathrm{Db_t} = 0.1\mathrm{Dp} + 0.9\mathrm{Db_i}, \quad \text{where}$$

Db_t is the threshold bulk density indicating that 10% total soil porosity has been lost, Dp is the mean particle density, given as 2.65 Mg m^{-3}, and Db_i is the initial bulk density, representing the soil found under undisturbed or ‘‘natural conditions’’.

This formula was applied to determine the extent of detrimental compaction in each of the 9 treatment units. Within each unit, Db_i was determined as the mean non-skid trail bulk density measured during the pre-treatment sampling period, and 2.65 Mg m^{-3} was used as Dp. Within each treatment unit, the mean bulk density measured at each plot during the post-treatment sampling was compared to the threshold bulk density. Of the 20 plots in each unit, the number exceeding the threshold was used to determine the percent aerial extent of detrimental compaction following the fuel treatments.

2.5. Statistical analysis

Treatment effects on soil properties were evaluated using analysis of covariance (ANCOVA). To remove the influence of pre-treatment differences among treatment groups, the pre-treatment data was modeled as a covariable (Selvin, 1995). Interaction effects were tested by adding a crossed (treatment × pre-treatment) term. Differences were considered significant at the $p < 0.05$ level. Analysis of variance (ANOVA) was used to assess treatment effects on the extent of detrimental compaction. In all comparisons, if differences among treatments were significant, the Tukey–Kramer HSD test was used to make multiple comparisons among treatment groups (Sall et al., 2001). Normality of treatment group means and homogeneity of variance among means were assessed using the Shapiro–Wilk test and O’Brien’s test, respectively. All analyses were conducted using JMPIN statistical software version 4.0.4 (SAS Institute, Inc.).

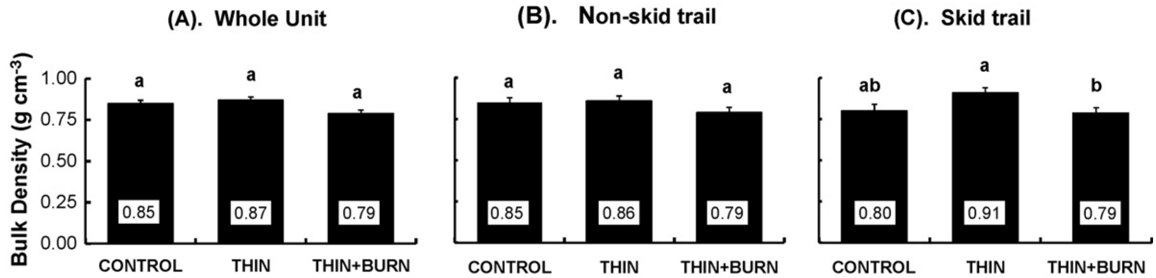

Fig. 1. ANCOVA comparisons of post-treatment soil bulk density by fuel treatment for (A) the mean bulk density within each treatment unit, (B) the mean bulk density based solely on non-skid trail areas, and (C) the mean bulk density based solely on skid trail areas.

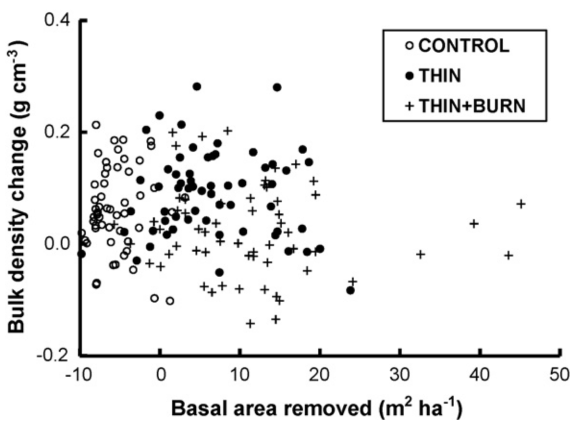

Fig. 2. Relationship between the change in soil bulk density following fuel treatments and the total basal area of trees removed by the treatments.

3. Results

3.1. Soil bulk density

When examined at the treatment unit scale, soil bulk density in the mechanically harvested treatments did not significantly differ from the Control (Fig. 1A). Mean bulk density values ranged from 0.79 to 0.87 g cm^{-3}. Similarly, when only the non-skid trail areas were compared, there were no significant differences in bulk density among the treatments (Fig. 1B), and mean values ranged from 0.79 to 0.86 g cm^{-3}. When only the skid trail areas were compared, neither the Thin or Thin + Burn differed significantly from the Control, but skid trails in the Thin treatment had significantly higher bulk density than those in the Thin + Burn (Fig. 1C). Mean values ranged from 0.79 to 0.91 g cm^{-3}.

Regression analysis was used to examine the relationship between changes in soil bulk density following the fuel treatments and the total basal area of trees removed by the treatments (Fig. 2). Correlation among the variables was poor, and no significant relationship was detected. Generally, the greatest levels of basal area reduction occurred in the Thin + Burn plots, but this did not correspond with the greatest changes in soil bulk density. The changes in basal area and bulk density for Control plots reflect year-to-year measurement differences.

3.2. Soil strength

At the treatment unit scale, soil strength in the Thin + Burn treatment was significantly greater than both the Control and Thin treatments (Fig. 3A). Mean soil strength in the Thin + Burn treatments was 23% greater than the Control mean, and 18% greater than the Thin mean. When only the non-skid trail areas were compared, there were no significant differences in soil strength among treatments (Fig. 3B), with mean values ranging from about 840 to 870 kPa. When only the skid trail areas were compared, trails in the Thin + Burn treatment had significantly higher soil strength than both the Control and Thin treatments (Fig. 3C). Mean soil strength of skid trails in the Thin + Burn treatments was 45% greater than the Control mean, and 26% greater than the Thin mean.

Regression analysis was used to examine the relationship between soil strength and soil bulk density at the plot scale (Fig. 4). Although the slope and intercept of the fitted line are significantly different than zero, almost none of the variability in soil strength was explained by changes in bulk density ($r^2 = 0.02$). At the individual plot level, both the greatest soil

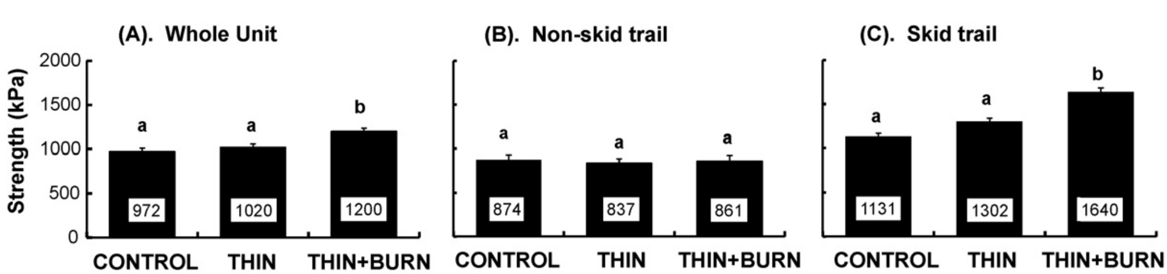

Fig. 3. ANCOVA comparisons of post-treatment soil strength by fuel treatment for (A) the mean strength value within each treatment unit, (B) the mean strength value based solely on non-skid trail areas, and (C) the mean strength value based solely on skid trail areas.

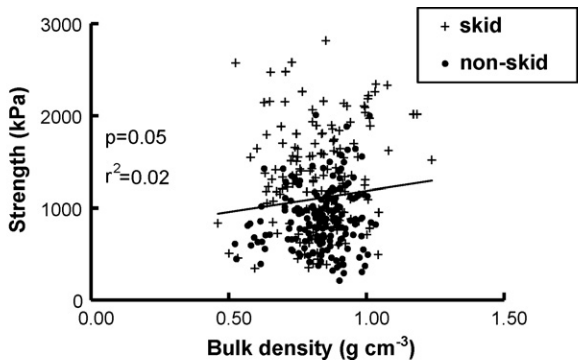

Fig. 4. Relationship between soil strength and soil bulk density following fuel treatments.

strength and greatest bulk density values were measured in skid trail areas.

In Fig. 5, soil strength is plotted against depth for skid trail and non-skid trail areas. Measurements were recorded at 1.5-cm intervals, to a maximum depth of about 60 cm. Throughout these profiles, the skid trail areas show a distinct increase in soil strength compared to the non-skid trail areas. On average, at any given depth the mean penetration resistance in skid trails was 485 kPa greater than the non-skid areas. The greatest differences were observed from about 6 to 20 cm depth, where the soil strength in skid trails measured between 600 and 750 kPa greater than the non-skid areas.

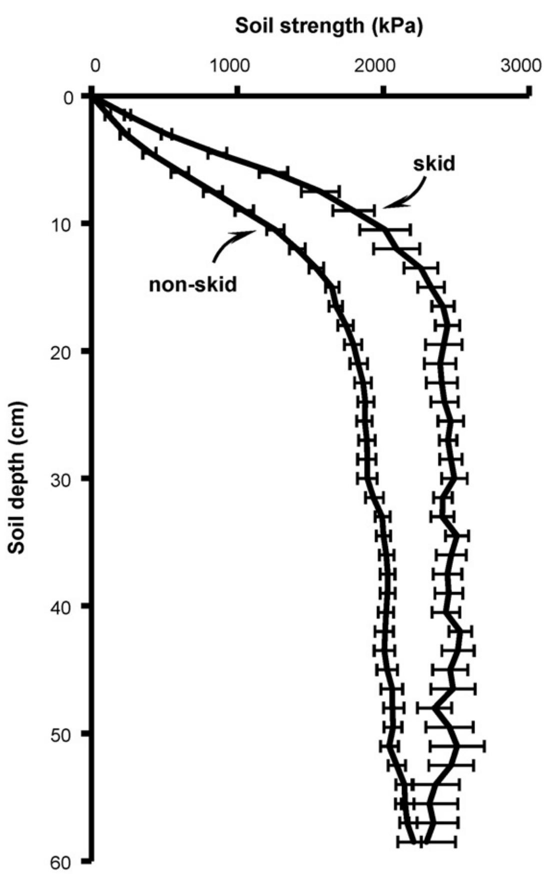

Fig. 5. Soil strength profiles for skid trail and non-skid trail areas following fuel treatments. Measurements were recorded at 1.5-cm intervals. Each point represents the mean of 9 units (3 each of Control, Thin, and Thin + Burn). Error bars show standard error.

Table 2
Extent of detrimental compaction following fuel treatments

	Percent detrimental compaction		
	Control	Thin	Thin + Burn
Replicate 1	0	0	0
Replicate 2	15	0	10
Replicate 3	0	20	5
Mean	5a	7a	5a

Mean values in a row followed by the same letter are not significantly different ($p > 0.05$).

3.3. Soil porosity and detrimental compaction

The extent of detrimental compaction, based on the USFS threshold methodology, is shown in Table 2. Within each treatment type, there was at least one unit with no detrimental compaction, while the remaining units each contained several plots that exceeded the compaction threshold. Of the 20 plots in each treatment unit, as many as 4, or 20%, exceeded the USFS compaction threshold for the unit. On average, 5, 7, and 5% detrimental compaction was observed in the Control, Thin, and Thin + Burn treatments, respectively. The mechanical treatments did not significantly change the extent of detrimental compaction compared to the Control treatment.

4. Discussion

4.1. Soil bulk density

There was no significant effect of the mechanical fuel treatments on soil bulk density. All units, including the Controls, had been logged with at least one commercial harvest in the past, and all contained a network of skid trails. The commercial harvest portion of the fuel treatments largely used existing landings and the associated skid trail network. Mastication had not been implemented in these stands prior to these fuel treatments, and the masticator traveled off of skid trails to treat non-merchantable materials. To assess the effects of the mastication treatment, ANCOVA was performed solely on the non-skid trail portions of the units. There was no treatment effect on the soil bulk density of these non-skid areas. About 550–600 trees were masticated per hectare as part of the mechanical treatments (Table 1; Stephens and Moghaddas, 2005b). The masticated residue was broadcast away from the machine, creating a debris bed of variable thickness. This debris likely cushioned the compacting forces of the masticator, which was mounted to a track-laying excavator. Mastication operations generally occurred in the summer period when the soil was relatively dry and more resistant to compaction. ANCOVA was also performed solely on the skid trail samples. While neither fuel treatment increased skid trail bulk density relative to the Control, bulk density of skid trails in the Thin treatment was significantly greater than in Thin + Burn. Group selection harvests were implemented in 2 of the 3 Thin units during the fuel treatment harvest. While the group selection areas were not measured for this study, the group selection materials were likely removed using the same skid trail network as the fuel treatment materials. This additional volume may have required more passes by the skidder, and may have contributed to the greater bulk density in skid trails of the Thin treatment. No group selection harvests were implemented in the Thin + Burn units during the fuel treatments.

The amount of material removed during a timber harvest will influence the number and extent of passes needed for skidding and other harvesting equipment (Stokes et al., 1995). This in turn will affect the amount of soil disturbance, displacement, and compaction. McIver and McNeil (2006) showed significant positive correlations between the change in tree density due to logging operations and both soil disturbance and soil displacement. Following the fuel treatments in our study, the level of tree removal and changes in soil bulk density were determined at each plot. The relationship between basal area removed and bulk density change for each treatment type was poor. Correlations were not improved by considering plots from each treatment in isolation. The greatest removals of basal area were observed in plots from the Thin + Burn treatment. This may have been due to thinning effects of the prescribed fire treatment, which would result in additional reductions of live trees by secondary mortality. Similar regression analyses were conducted using the volume and number of stems per hectare removed. In all cases, these harvest metrics were poor indicators to predict changes in either soil bulk density or soil strength.

4.2. Soil strength

At the treatment unit scale, the Thin + Burn treatment significantly increased soil strength relative to the Control and Thin treatments. Thin had no significant treatment effect. To determine whether the increase in soil strength in the Thin + Burn units was attributable to the skid trails or non-skid trail areas, separate ANCOVA analyses were conducted for each of these sample types. The treatment comparison based solely on the non-skid trail areas show that there was no treatment effect on soil strength in these portions of the units. Because masticators travel throughout the treatment unit, there is reasonable concern that they can cause extensive compaction. However, these soil strength results further support the suggestion above that mastication did not result in compaction away from the skid trails. We could find very little research examining the effects of mastication on soil compaction. Following forest thinning in the Lake Tahoe basin in California, Hatchett et al. (2006) compared soil strength directly in masticator tracks with strength at varying distances from the tracks. They found that mastication with heavy equipment did not cause soil compaction at most soil depths. Mastication impacts on soil compaction were only detected at the 10- and 25-cm depths, and in those cases only when the path of the machine track was compared to areas approximately 6 m away. Their findings suggest that any compaction was dispersed a broad distance from the actual machine travel path, and limited to a narrow range of soil depth.

The ANCOVA analysis based solely on the skid trail areas shows that the Thin + Burn treatment resulted in skid trails with greater soil strength than either the Control or Thin treatments. When the whole treatment unit was considered, the Thin + Burn had increased soil strength compared to the other treatments. This increase was due to greater impacts concentrated on skid trails, rather than compaction impacts distributed throughout the treatment unit.

4.3. Relationship between soil strength and bulk density

Soil strength is strongly affected by soil moisture content and soil bulk density (Vazquez et al., 1991; Vaz and Hopmans, 2001). Numerous authors have reported a positive relationship between soil strength and bulk density (e.g., Sands et al., 1979; Allbrook, 1986; Clayton, 1990; Miller et al., 2004). In some instances, the relationship is linear (House et al., 2001; Miller et al., 2001), while it is curvilinear in others (Unger and Kaspar, 1994; Ampoorter et al., 2007). In addition, some authors analyze soil strength as the dependent variable, and others as the independent variable. We chose to represent soil strength as dependent on soil bulk density, and the relationship between them was poor. Only 2% of the variability in soil strength could be explained by changes in bulk density. Samples collected in skid trails clearly differ from those in the non-skid areas. While the range of bulk density did not differ strongly between the two groups, the soil strength of the skid trail samples was primarily clustered in the higher strength ranges, and the non-skid samples clustered in the lower strength ranges. Despite the increased soil strength observed in the skid trails, strength could not be easily predicted based on bulk density values. Vazquez et al. (1991) reported that soil strength is a more sensitive indicator of soil compaction than bulk density after observing large increases in strength and only minor increases in bulk density. Our measurements also suggest that soil strength is more sensitive to change following mechanical fuel treatments. The usefulness of either compaction metric to the forest manager or soil scientist will depend on actual, site-specific compaction effects on productivity, soil ecological processes, or other measures of "forest health."

4.4. Soil strength—depth profiles

Mean soil strength in skid trails was consistently greater than non-skid trail areas for all recorded depths. While skidder operations and traffic is clearly a surface disturbance, the machine effects are distinguishable nearly 60 cm below the surface. The strength increase in the skid trails was greatest near the soil surface. For example, in the upper 6 cm, skid trail strength was more than double the non-skid trail strength. This relative increase declined rapidly with depth. At 12 cm, the mean skid trail strength was 50% greater than non-trail strength, and lowered to 30% at about 20 cm depth. On sandy soils, Ampoorter et al. (2007) found that machine traffic most increased soil strength in the 20–50 cm interval rather than the surface. They suggested that the machine wheels caused some loosening of the surface soil, reducing its strength and resistance to penetration. Such surface loosening of the upper 20 cm was not apparent in the sandy loam soils of our study site. In our study, the greatest differences in soil strength between skid trails and non-skid trail areas were not observed at the surface, but rather several cm below ground. In addition to possible loosening at the surface, organic matter in the surface layer likely provided a buffer against increased compaction. The upper 15 cm of mineral soil contained more than 50 g kg^{-1} total carbon (C), which helped resist deformation and compaction. Soil C rapidly declined with depth, and the 15–30 cm layer typically contained about 25 g kg^{-1} total C.

4.5. Soil porosity and detrimental compaction

Active forest management and manipulation necessarily has some impact, from very small to very large, on the underlying soils. Grigal (2000) states, ‘‘To foster communication, a threshold should be established above which effects merit attention and below which further consideration is not justified’’. The USFS was at the forefront of developing such standards, guidelines, and thresholds to serve as first warnings that forest activities may be detrimental to soil productivity (Page-Dumroese et al., 2000). In 1995, the USFS Pacific Southwest Region established a threshold to help prevent detrimental compaction and subsequent loss of inherent soil productivity. The USFS Regional compaction threshold is based on the loss of total soil porosity, but application of the USFS guidance is based on increases of soil bulk density as a proxy for porosity loss. While bulk density is not a measure that directly controls root growth, it is often related to factors that have direct impacts on root growth, such as gas diffusion, water availability, and mechanical resistance (Miller et al., 2004).

Despite the commercial harvest, skidding activities, and unit-wide mastication, ANOVA comparisons indicate that the Thin and Thin + Burn treatments did not change the extent of detrimental compaction relative to the Control. Prior to implementation of this fuel treatment study, most of the units had been harvested 2 times in the last 20 years. During this third harvest entry, existing primary skid trails were re-used where feasible. This minimized the creation of new skid networks and helped to prevent extensive detrimental compaction. The small-diameter, non-merchantable materials had not previously been treated in these units. Although the masticator largely operated off of skid trails, mastication did not cause any apparent increase in the extent of detrimental compaction. This was likely due to the buffering effects of the debris bed created from the masticated materials and upon which the masticator traveled.

5. Conclusion

Soil compaction is an important management indicator for forest site productivity (Poff, 1996; Powers, 1999; De Vos et al., 2005). In managed timberlands, compacted soils often occur in skid trails and landings. In dry forests, many of these stands are being considered for large-scale fuel reductions that are unlike most previous silvicultural treatments in these areas. In addition to stand thinning from below, huge quantities of non-merchantable materials are being prescribed for removal or mastication. In this study, a masticator operated throughout the Thin and Thin + Burn treatment units, but did not significantly increase soil bulk density or strength in the non-skid trail areas. The masticated residues created a debris bed that may have provided a buffer against compaction. There were no treatment effects on the extent of detrimental compaction, defined by the USFS Regional threshold as a 10% reduction in soil total porosity. Detrimental soil compaction can be minimized and cumulative impacts of compaction can be curtailed by the re-use of existing skid trails and transportation networks during fuel treatments in these heavily managed stands.

The immediate need to treat forest fuels is often justified as a need to improve or maintain forest health. As such, strategies for large-scale fuel treatment operations must consider long-term impacts on a range of ecosystem components, including forest soils. For fuel treatments to remain effective over time, they must be maintained (Van Wagtendonk, 1996; Weatherspoon, 1996; Greenlee and Sapsis, 1996; Agee et al., 2000; Ingalsbee, 2005). This may require repeated mechanical entries over the life of the stand. In this study, frequent harvest entries in the last 2 decades did not result in increases in soil bulk density, strength, or extent of detrimental compaction. While forests are resilient systems, care must be used to manage the level of disturbance created with each entry. To the extent possible, subsequent harvests using heavy skidding equipment should rely on existing disturbance pathways, allowing for recovery and subsequent productivity enhancement between entries.

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