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Effect of thinning and soil treatments on *Pinus ponderosa* plantations: 15-year results

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This paper is dedicated to the memory of Dr. Robert F. Powers who initiated this experiment.

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ABSTRACT

Thinning with removal of whole trees in a plantation or natural forest stand raises two main concerns – soil compaction from the ground-based machinery and nutrient depletion particularly with whole tree harvest as is often practiced for attendant fuels reduction. To address these concerns, two sets of experimental treatments were imposed in young ponderosa pine plantations. In the first set, we applied four treatments to test the effects of thinning with biomass removal using progressively more soil manipulations: (I) control, (II) thinning only with all biomass removed, (III) same as (II) but followed by sub-soiling in traffic lanes, and (IV) same as (III) but with nitrogen and phosphorus fertilization within traffic lanes prior to sub-soiling. In the second experiment set we applied four combination treatments to test the further effects of soil manipulations with wood chips and fertilizer on traffic lanes. In thinned stands: (i) the harvested trees were chipped, and spread onto traffic lanes followed by sub-soiling and rototilling, (ii) same as (i) but traffic lanes also received N and P with the chips prior to the sub-soiling, (iii) traffic lanes were sub-soiled, then thinning chips were returned to just the surface of traffic lanes, and (iv) same as (iii) but traffic lanes also received N and P fertilizer with the chips. Tree height and diameter were measured three times, starting immediately following treatments and again at 5 and 15 years post-treatment. In addition, soil bulk density was measured at 6 years and soil chemistry (C, N, and P) was measured at 6 and 16 years. Our results indicate: (1) thinning by itself with no subsoiling did not compact the soils, but increased growth rate of residual trees, although the periodic annual increment of basal area and volume was still higher in the control than other main-plot treatments; (2) neither subsoiling nor rototilling, both of which might mitigate soil compaction, enhanced tree growth; (3) short-term plantation growth was not improved with chip returns or chips with fertilization; (4) since thinning and soil treatments showed more insect damage and higher mortality, any management operations that involve cutting or damaging trees or roots should be avoided during active periods of bark beetle flight; (5) both thinning and soil treatments did not reduce carbon sequestration in the mineral soils. A lack of growth benefits from returning thinning chips, rototilling, and direct fertilization for a longer period appeals to further study.

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1. Introduction

Managing forest plantations for high quality wood products often includes thinning to increase residual tree growth while simultaneously extracting biomass for energy or wood products. Ground-based heavy equipment used for the thinning has been shown to compact soil and may affect site productivity (Cambi et al., 2015; Morris and Miller, 1994; Powers et al., 1990; Sands et al., 1979). In natural forests, fuel reduction thinning or other forest restoration projects also face similar soil disturbance concerns (Moghaddas and Stephens, 2007, 2008; Page-Dumroese et al., 2010a,b). Numerous studies have shown that compaction persists for decades on skid trails on volcanic and granitic soils (Froehlich et al., 1985; Vora, 1988). Cumulative impacts of soil compaction over multiple rotations were shown for sandy soils in Australia (Sands et al., 1979) and for silt loams in Louisiana (Tiarks and Haywood, 1996). Soil compaction clearly persists. But, its effect on tree productivity has mixed results (Miller et al., 2004); various research has shown a positive effect (Gomez et al., 2002), no effect (Miller et al., 2010; Holub et al., 2013), and a negative effect (Geist et al., 2008; Murphy et al., 2004) from ground-based timber harvest. The discrepancy appears to relate to soil type and various

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topographic characteristics (Gomez et al., 2002; Powers et al., 2005; Reeves et al., 2012).

Whole-tree harvesting raises nutrient concerns as well (Powers et al., 2005; Ponder et al., 2012). When trees are thinned from a plantation or a natural stand, a significant amount of nutrients can be removed, particularly in the nutrient-rich crown foliage. Although the thinning increases nutrient availability for residual trees (Smethurst and Nambiar, 1990), subsequent high demand of nutrients due to the post-thinning leaf area growth (Ritchie et al., 2013) may cause temporary depletions of soil nutrients and temporary reductions in net primary productivity (Powers et al., 1990, 2005). However, many previous growth and yield studies demonstrate that a moderate thinning of an existing ponderosa pine stand would at least maintain the growth, if not increase it, as compared to unthinned stands (Zhang et al., 2013a,c). Results from the Long-Term Soil Productivity study network showed that young stand growth on whole-tree harvest plots did not significantly differ from growth in stem only harvest plots across various species, at least for the first ten years (Powers et al., 2005; Ponder et al., 2012).

In this study, we used the data from a well-designed study established on young plantations following a pre-commercial thinning. Several treatments were imposed, aiming to answer the following questions: (1) did mechanized thinning compact the soil? (2) Did tillage mitigate it? (3) Did whole tree harvest deplete the nutrients? (4) Did chip returns and fertilization mitigate nutrient depletion? And (5) was tree growth affected? We hypothesized that (a) mechanical thinning causes soil compaction; compaction reduces infiltration and root growth, and this would be observed as decreased tree growth. (b) Whole-tree harvesting removes sources of soil organic matter and nutrients, ultimately degrading soil fertility and water holding capacity, and therefore reduces tree growth.

2. Materials and methods

2.1. Study site

The study was installed in 14- or 15-year-old ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson) plantations in 1998. The study site was located near Pondosa, California (41°12′N Lat. and 121°37′W Long.) at 1160–1270 m elevation on Roseburg Resources land east of Mt. Shasta. The study site was part of a 2250 ha pine forest planted between 1981 and 1986 following the 1977 Pondosa Fire. Precipitation, mostly as snow, averaged 760 mm annually. Soils are fine-loamy Vitrandic Palexeralfs of the Jimmerson series, formed from andesitic lava flows. Surface textures ranged from loam to stony sandy loam, with generally less than 5% rock content in the topsoil, excluding surface and subsurface boulders which are common at the site. Trees were mechanically planted in rows at about a 2.4 m by 3.0 m spacing. Seedling survival was very high. Crowns had closed after a decade in most of the plantation and a thinning was needed to sustain tree growth and vigor and to reduce fuels in this fire-prone area.

These plantations were mechanically thinned using a 3-wheeled Morbark Wolverine™ shear and grapple skidder. Every third row was entirely removed, as were about half of the trees from the two adjacent rows. This left a residual density of 370–445 trees per ha; the thinning intensity was chosen based on tree size and stand density aiming to obtain commercial products on the next entry based on the company's growth model. The clear-cut rows were concurrently used for traffic lanes for removing the cut tree stems. Biomass of the whole trees was chipped offsite and utilized for cogeneration energy production. The entire operation was a normal industrial timber management project, and this study was designed on it. The research installation was conducted in July of 1998 when soil was relatively dry.

2.2. Study design

Four main effect treatments were applied to four 0.4-ha plots within each of four blocks with a total of 16 plots (experimental units). In a second experiment, four sub-effect (after thinning with thinning chip returns) treatments were applied to four 0.1-ha plots (16 plots total) adjacent to the main effect plots (Fig. 1).

- Main effect treatments:
  - I. Control: no treatment.
  - II. T: thinning only and all biomass removed.
  - III. T/S: thinning followed by sub-soiling in traffic lanes.
  - IV. T/F/S: thinning followed by N/P fertilization in traffic lanes and sub-soiling.

For the two sub-soiling treatments (III and IV), traffic lanes were tilled along wheel tracks to a depth of about 0.5 m using one pass of a winged sub-soiler drawn by a crawler tractor (Fig. 1). Fertilization was applied using granular urea and ammonium triple phosphate at 224 kg N ha^{-1} and 336 kg P ha^{-1} in the traffic lanes prior to subsoiling. Tillage provided an opportunity to work N and P into the rooting zone of residual trees, as well as mitigate compaction.

- Sub-effect treatments:
  - i. T/C/S/R: Thinned trees were chipped, returned and spread on traffic lanes, then sub-soiled and rototilled.
  - ii. T/C/F/S/R: same as (i) but traffic lanes also received N and P with the chips prior to the sub-soiling and rototilling.
  - iii. T/S/C: Traffic lanes were sub-soiled, then thinning chips were returned to just the surface of traffic lanes.
  - iv. T/S/C/F: same as (iii) but traffic lanes also received N and P with chips.

Some of the rationales for these treatments are as follows. Retention of woody residues as chips was to reduce ladder fuels while retaining site organic matter and improving soil water storage capacity. Entire trees were chipped, including crown foliage. The purpose of chip fertilization was an attempt to lower the C/N ratio to favor microbial decomposition. The sequence of sub-treatments, such as subsoiling before or after spreading chips, produced different outcomes reflecting management scenarios of interest, with different costs and presumed added-benefits for subsequent soil quality and tree growth.

2.3. Tree measurement

After the study was installed, an inner 0.2-ha square for the main-effect treatments and inner 0.05-ha square for sub-effect treatments were established as measurement plots and all trees within these measurement plots were tagged. Diameter at breast height (1.37 m) was measured in 1998, 2003, and 2013 using a marked staff for height precision. Height measurements were taken for every fifth tree (20% sample) using a height pole and spotter. From these measurements, we calculated basal area and estimated individual-tree volume using a volume equation developed in northern California (Oliver and Powers, 1978). From these individual tree data, we calculated average tree height, quadratic mean diameter (QMD), basal area (BA), and volume for each plot. Then, we calculated periodic annual increment (PAI) for QMD (cm yr^{-1}), average height (m yr^{-1}), BA (m^2 ha^{-1} yr^{-1}), and volume (m^3 ha^{-1} yr^{-1}) using net increase, that is, the change based on values at the end of the measurement period relative to those at the start of the measurement period. PAI was used to account for differences in plot level stocking and/or tree metrics at the initiation of the study.

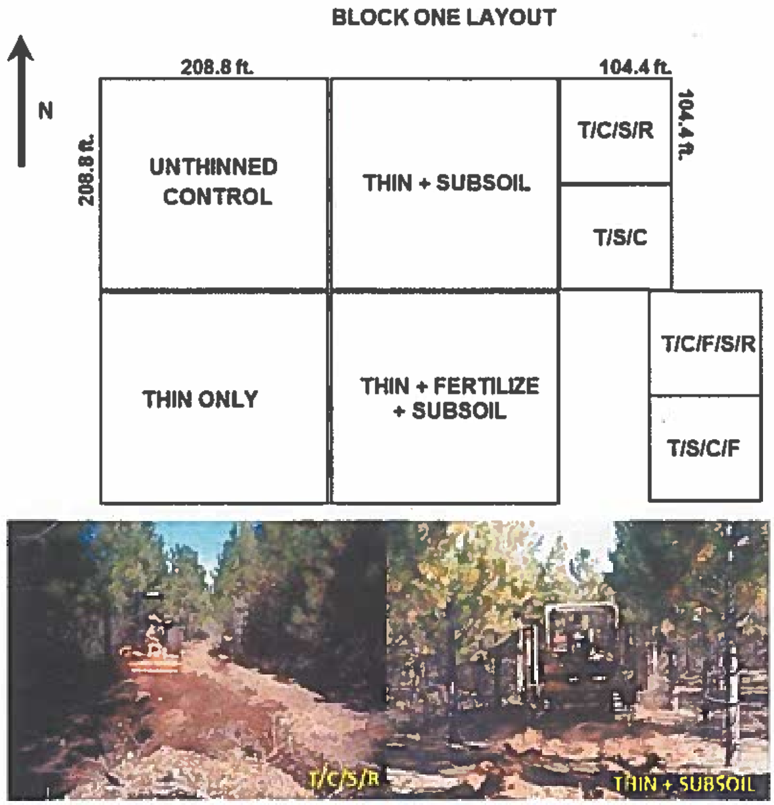

Fig. 1. Block layout for the main-effect and the sub-effect treatment plots including control and various treatment combinations of thinning (T), sub-soiling (S), fertilization (F), chip returns (C), and rototilling (R). Left photo (T/C/S/R) shows a cultivator to rototill the chips and right photo shows sub-soiling operation.

2.4. Soil sampling and analysis

Soil samples were collected from three depths (0–10, 10–20, and 20–30 cm) for soil physical and chemical analyses, using a volumetric core sampler in 2004. Ten samples were randomly chosen in each control plot; 20 samples were collected from T, T/S, and T/F/S plots, 10 from traffic lanes and 10 from the adjacent tree rows in paired fashion. In the sub-effect treatment plots, five samples were randomly chosen from within traffic lanes only. The soil total bulk density, fine bulk density, and porosity were determined for these 1080 samples.

Samples were collected using a hammer-driven, double-wall, soil core sampler. Soil cores 5.34 cm diameter by 6.00 cm length were centered on the 5, 15, and 25 cm depths to represent the three soil depths, respectively. Soil samples were returned to the lab and dried at 105 °C to a constant weight. The samples were next weighed before being sieved through a 2-mm sieve. Rock fragments were weighed. Total bulk density (D_{bt}, Mg m^{-3}) was calculated by dividing the oven-dry mass by sample volume:

$$D_{bt} = W_s/V_t \quad (1)$$

where W_s is oven-dry mass of the sample (Mg) and V_t is total volume of the sample including pore volume and solid volume m^3.

Fine soil bulk density D_{bf} was calculated by:

$$D_{bf} = D_{bt}(1 - g_r)/(1 - v_r) \quad (2)$$

where g_r is gravimetric rock-fragment content that was calculated by dividing the mass of rock fragment by total sample mass. Volumetric rock-fragment content (v_r) was calculated by:

$$v_r = D_{bt}(g_r/D_{br}) \quad (3)$$

where rock-fragment density (D_{br}) was assumed to be 2.65 Mg m^{-3}.

Total porosity PS (% volume) was calculated by:

$$PS = 1 - D_{bt}/D_{br} \quad (4)$$

Soil chemistry was analyzed by pooling samples from the same depth within each plot, separated by traffic lanes and adjacent tree rows where applicable. Samples collected in 2014 were only for chemistry analysis. Five samples were collected from control, traffic lanes, and adjacent undisturbed tree rows in the same fashion as in 2004.

Soil P was analyzed with the Bray-P1 method (Bray and Kurtz, 1945). To determine total soil N and C these samples were also analyzed using LECO Tru-Spec CN analyzer (Leco Corp., St. Joseph, MI, USA). Concentrations were then converted to total N, P, and C weight (Mg ha^{-1} or kg ha^{-1}) using average fine bulk density per depth per plot. The 2004 fine bulk density was also used for the 2014 calculations.

2.5. Insect damage and mortality

At each measurement, the tree condition was recorded for each tree including good crop tree, forked, insect damage, mechanical damage, dead top, dead, etc. Any trees with any dead foliage, branches, or bole pitch tubes attributed to insect attack were recorded as insect damage. Insect damage and mortality were calculated by dividing numbers of damaged or dead trees by total trees in the plot.

2.6. Statistical analysis

All variables were analyzed based on a randomized complete block design with treatments as the fixed effect and block as a random effect using SAS PROC GLM (SAS Institute Inc., 2012). Because

Table 1
Post treatment means and standard errors ($\mu \pm SE$) and probability (Pr > F) of testing H_0: $\mu_1 = \mu_2 = \mu_3 = \mu_4$ for trees per hectare, quadratic mean diameter (QMD), tree height, basal area (BA), and volume (Vol) measured immediately after treatments were applied in 1998.

Treatment	Trees (ha^{-1})	QMD (cm)	Height (m)	BA ($m^2\ ha^{-1}$)	Vol ($m^3\ ha^{-1}$)
Main-effect					
Control	1354 (67)^a	15.3 (1.0)	5.9 (0.6)	24.6 (2.2)^a	50.9 (9.1)^a
T	429 (8)^b	16.6 (1.0)	6.3 (0.6)	9.4 (1.1)^b	20.7 (4.1)^b
T/S	414 (16)^b	16.4 (0.3)	6.2 (0.4)	8.8 (0.3)^b	18.7 (1.7)^b
T/F/S	453 (13)^b	16.5 (1.0)	6.2 (0.6)	9.8 (1.1)^b	21.1 (4.1)^b
Pr > F	<0.001	0.164	0.144	<0.001	<0.001
Sub-effect					
T/C/S/R	484 (29)	15.8 (0.3)	6.0 (0.4)	9.5 (0.6)	19.6 (2.2)
T/S/C	435 (23)	16.3 (0.8)	6.2 (0.5)	9.1 (1.0)	19.6 (3.7)
T/C/F/S/R	435 (31)	17.1 (1.3)	6.4 (0.6)	10.0 (1.3)	22.4 (5.0)
T/S/C/F	455 (35)	17.4 (0.4)	6.6 (0.4)	10.8 (0.9)	23.9 (2.7)
Pr > F	0.227	0.235	0.307	0.214	0.295

T = thin; S = sub-soiling; F = fertilization with N and P; C = chips returned; R = rototilled. Means with different letter within significant main-effect treatments indicate difference at $p < 0.05$. No comparisons were conducted within non-significant main- or sub-effect treatments.

main effect treatment plots (0.4 ha) and sub-effect treatment plots (0.1 ha) were separately assigned to their respective blocks randomly, they were separately analyzed using the same base model:

$$y_{ij} = \mu + \alpha_i + \gamma_j + \varepsilon_{ij} \quad (5)$$

where y_{ij} is the dependent variable measured for the *i*th treatment and the *j*th block, μ is the overall mean, α_i is the fixed effect of the *i*th treatment ($i = 1, 2, 3,$ and 4), γ_j is the random effect of the *j*th block ($j = 1, 2, 3,$ and 4), $\gamma_j \sim N(0, \sigma_B^2)$, and ε_{ij} is an experimental error, $\varepsilon_{ij} \sim iidN(0, \sigma_e^2)$.

We used this base model for analyzing the 1998 stand density (trees per hectare), QMD, height, basal area, and volume (Table 1), as well as the 2003 insect damage and mortality. Then, repeated measures of analyses of variance were conducted for the post-treatment PAI height, QMD, BA, and volume during 1998–2003 and 2003–2013 periods using 1998 data as a covariate because of the existing differences in tree size among plots when treatments were applied.

Soil total bulk density, fine bulk density, and soil porosity were derived from soil volume, dry weight, and rock content in 2004. So, we used the base model by substituting for one treatment factor with two factorial factors with *i*th treatment, *k*th soil depth ($k = 1, 2,$ and 3), and their interactions as fixed effects.

For soil chemical analyses (total N, C, P, and C/N), different sampling years were treated as a repeated measurement. Not only were depth and treatment by depth interactions added into the model, the repeated measure ANOVA was used to test period effect.

For each analysis, residuals were examined to ensure that statistical assumptions of normality and homoscedasticity were met. If not, a natural log or square-root transformation was applied. Multiple comparisons among treatments or depths were conducted for least squares means by the Tukey–Kramer test by controlling for the overall $\alpha = 0.05$. If a covariate was used in the model, we presented least square means and standard errors in the results. Otherwise, we presented treatment means and standard errors.

3. Results

3.1. Tree growth

Trees varied significantly ($p < 0.01$) in density (trees per hectare), basal area (BA), and volume among main effect treatments in 1998 (Table 1). These differences mainly occurred in the control where no trees were removed compared to the other treatments. Generally, control plots had three times the number of trees, and double the basal area and volume as compared to other treatment plots. Height and QMD were not significantly different among main effect treatments ($p > 0.14$), however controls were over 1 cm smaller in stand level diameter and 30 cm less in height (Table 1). Similarly, although none of the variables were statistically significant among sub-effect treatments in 1998, the variation among the sub-treatments at the start of the experiment, if real, may have still affected future growth, in that larger trees presumably have more leaf area and thus more capacity to produce biomass, independent of treatment. Therefore, our analyses were focused on the periodic annual increment (PAI) using the 1998 base values as a covariate to minimize any effect of these starting differences.

Overall, differences in PAI-QMD, PAI-height, PAI-BA, and PAI-volume were found to be significant among main-effect treatments ($p < 0.04$) (Fig. 2). Year-by-treatment interactions were significant for PAI-QMD and PAI-height ($p < 0.02$). Among sub-effect treatments, we found only PAI-QMD varied significantly ($p < 0.05$). In addition, PAI-QMD also showed a difference in year by treatment interaction ($p = 0.04$). Although trees in controls showed less growth in QMD (0.65 and 0.35 cm yr^{-1}) and height (0.36 and 0.34 m yr^{-1}) for both periods (Fig. 2A and C), control PAI BA (2.61 and 1.68 $m^2\ yr^{-1}$) was still the highest because these plots carried about 3 times as many trees as in all thinned plots (Fig. 2E). A similar trend was also found for PAI volume (Fig. 2G). Sub-effect treatments, however, did not cause any significant difference in PAI for height, basal area, and volume (Fig. 2D, F, and H), indicating that fertilization, sub-soiling, or chip incorporation treatments did not affect stand-level growth in these plantations.

3.2. Insect damage and mortality

There were significant main-treatment effects in insect damage and mortality ($p < 0.01$) (Fig. 3). Insect damage was primarily red turpentine beetle (*Dendroctonus valens*) boring into boles of trees. Thin and post-thin treatments showed a significantly higher incidence of insect damage than controls (Fig. 3A). Yet, only the T/F/S treatment showed significantly higher mortality than others including controls (Fig. 3C). No significant difference in either insect damage or mortality was found ($p > 0.35$) among the sub-effect treatments (Fig. 3B and D).

3.3. Soil bulk density and porosity

Location effects between traffic lanes and non-traffic lanes were not significant in D_{bt}, D_{bf}, and porosity ($p > 0.17$). D_{bt}, D_{bf}, and

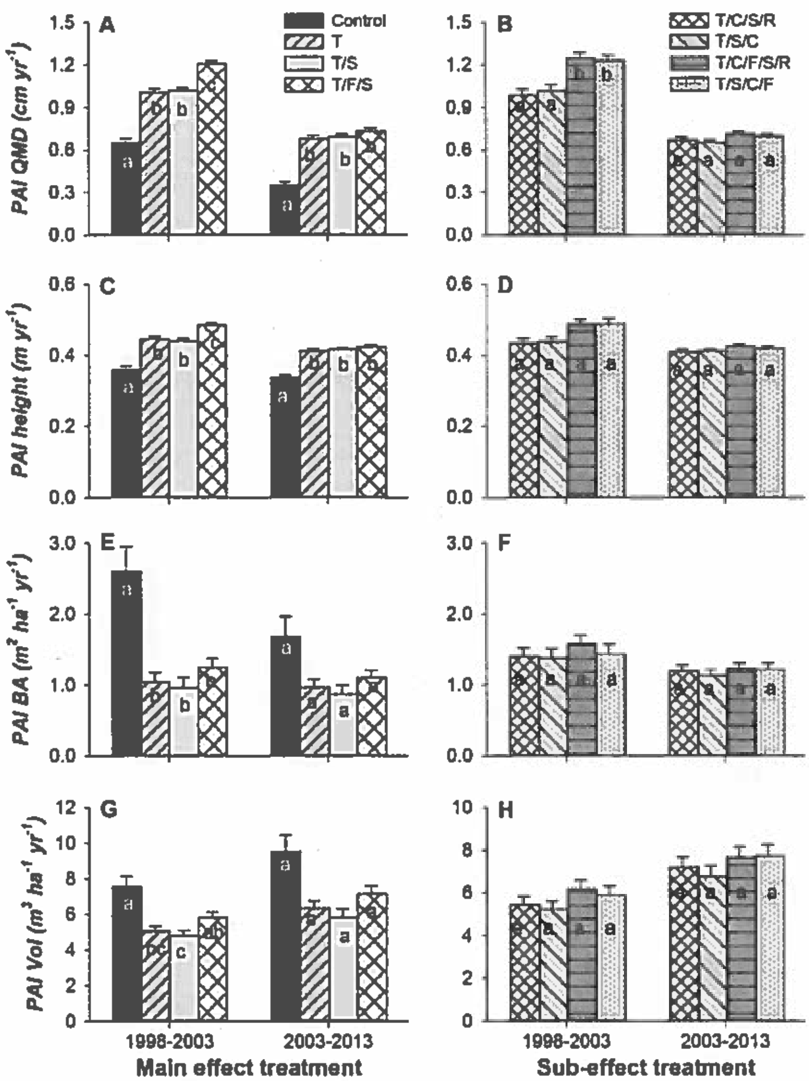

Fig. 2. Periodic annual increment (least square means and standard errors) for QMD, height, basal area, and volume of ponderosa pine grown in main-effect and sub-effect treatment plots including control and various treatment combinations of thinning (T), sub-soiling (S), fertilization (F), chip returns (C), and rototilling (R) during 1998–2003 and 2003–2013 growing periods. Means with different letter within either measuring periods indicate difference at $p < 0.05$.

porosity were 1.08 ± 0.01 Mg m^{-3}, 1.03 ± 0.01 Mg m^{-3}, and $56.05 \pm 0.58\%$ in the traffic lanes and 1.07 ± 0.01 Mg m^{-3}, 1.02 ± 0.01 Mg m^{-3}, and $56.45 \pm 0.55\%$ in the non-traffic lanes, respectively. None of the interactions between location and depth or treatment were significant. Therefore, location effect was not considered in the further analyses.

Significant differences between soil depths were found for total bulk density, fine bulk density, and porosity in both main-effect plots ($p < 0.01$) and sub-effect plots ($p \leqslant 0.03$) measured in 2004 (Table 2). Soil at 20–30 cm differed from others in the main effect plots, whereas in the sub-effect plots the only difference found was between 0–10 cm and 20–30 cm depths. All variables significantly varied only among the sub-effect treatments ($p < 0.01$). Multiple comparisons showed higher D_{bt} and D_{bf}, and lower porosity in T/S/C versus T/C/S/R and T/C/F/S/R plots, suggesting rototilling reduced bulk density. No significant differences were detected for any variables among treatment by depth interactions ($p > 0.36$). Notably, variation in absolute values among plots is small (D_{bt} 0.9–1.1) indicating homogeneous soils with little matrix rock content, and the pattern of increasing density with depth is typical for such Alfisols.

3.4. Soil carbon and nutrients

Differences were found to be significant in total P ($p < 0.01$), but not in total N ($p = 0.08$), C ($p = 0.26$), or C/N ($p = 0.74$) among main-effect treatments. Yet, N, C, and C/N differed significantly among depths and among year by depth interactions ($p < 0.05$), but P did not. Year effect was significant in N, P, and C/N ($p < 0.01$). No interactions were significant among other two-way or three-way interactions.

Among the sub-effect treatments, we found significant treatment effects in N ($p = 0.02$) and P ($p < 0.01$), as well as depth effect and year effect in N, C, and C/N (all $p < 0.01$). There were no significant two-way or three-way interactions among treatment, depth, and year.

Regardless of main treatments or sub-effect treatments, depth differences in N, C, and C/N generally occurred between 0–10 cm and other depths, with the top layer being more C and N enriched and having higher C/N ratios than lower depths (Table 3). The 2004 soil samples contained more N and P, less C and lower C/N than the 2014 soil did. Carbon accumulations were greater than 49 Mg ha^{-1} within the top 30 cm; increase rates were 5.1%, 2.8%, −4.7%, and

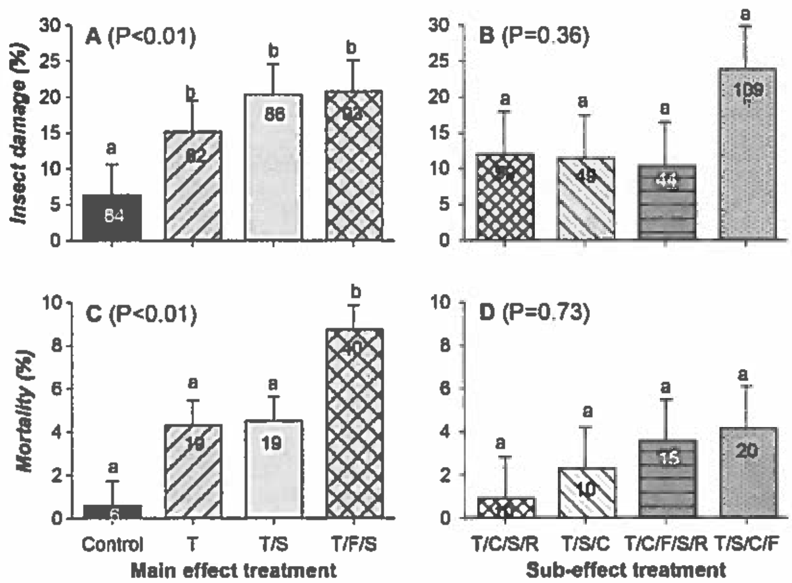

Fig. 3. Insect damage and mortality (least square means and standard errors) of ponderosa pine grown in main-effect and sub-effect treatment including control and various treatment combinations as thinning (T), sub-soiling (S), fertilization (F), chip returns (C), and rototilling (R) in 2003. *p*-values are the probabilities (Pr > F) of testing H_0: $\mu_1 = \mu_2 = \mu_3 = \mu_4$. Means with different letter indicate difference at $p < 0.05$. The numbers inside bars are average insect damage or mortality in trees per ha across blocks.

Table 2
Treatment means with standard errors ($\mu \pm$ SE) and probability (Pr > F) from ANOVA for total bulk density (D_{bt}), fine bulk density (D_{bf}), and porosity of soils collected at three depths under various treatments in 2004, six years after treatments were applied in 1998.

Treatment		Depth	D_{bt} (Mg m^{-3})	D_{bf} (Mg m^{-3})	Porosity (%)
Main effect	Control	0–10	1.05 (0.05)	1.01 (0.05)	57.3 (2.3)
		10–20	1.08 (0.03)	1.04 (0.03)	56.3 (1.4)
		20–30	1.11 (0.04)	1.06 (0.04)	55.0 (1.8)
	T	0–10	1.04 (0.03)	0.99 (0.03)	57.7 (1.5)
		10–20	1.08 (0.03)	1.02 (0.03)	56.4 (1.5)
		20–30	1.10 (0.03)	1.05 (0.04)	55.2 (1.5)
	T/S	0–10	1.04 (0.02)	0.99 (0.02)	57.9 (0.9)
		10–20	1.07 (0.02)	1.03 (0.03)	56.6 (1.2)
		20–30	1.10 (0.02)	1.06 (0.02)	55.5 (1.0)
	T/F/S	0–10	1.07 (0.02)	1.00 (0.02)	56.7 (1.0)
		10–20	1.09 (0.02)	1.03 (0.03)	56.0 (1.1)
		20–30	1.13 (0.02)	1.06 (0.03)	54.4 (1.1)
Pr > F	Treatment (Trt)		0.243	0.797	0.245
	Depth		<0.001	<0.001	<0.001
	Trt * Depth		0.999	1.000	0.999
Sub-effect	T/C/S/R	0–10	0.94 (0.06)	0.86 (0.08)	61.9 (2.8)
		10–20	1.03 (0.06)	0.95 (0.08)	58.1 (2.9)
		20–30	1.04 (0.06)	0.96 (0.08)	57.9 (2.9)
	T/S/C	0–10	1.07 (0.03)	1.00 (0.03)	56.7 (1.5)
		10–20	1.08 (0.05)	1.01 (0.06)	56.2 (2.3)
		20–30	1.12 (0.05)	1.05 (0.06)	54.6 (2.4)
	T/C/F/S/R	0–10	0.97 (0.05)	0.89 (0.06)	60.8 (2.3)
		10–20	1.03 (0.07)	0.96 (0.08)	58.4 (2.9)
		20–30	1.03 (0.05)	0.97 (0.06)	58.1 (2.4)
	T/S/C/F	0–10	1.04 (0.04)	0.98 (0.05)	58.0 (1.8)
		10–20	1.03 (0.04)	0.96 (0.05)	58.1 (1.9)
		20–30	1.03 (0.04)	0.97 (0.05)	58.1 (1.8)
Pr > F	Treatment (Trt)		0.001	0.001	0.001
	Depth		0.020	0.031	0.019
	Trt * Depth		0.467	0.369	0.463

T = thin; S = sub-soiling; F = fertilization with N and P; C = chips returned; R = rototilled.

Table 3
Soil total carbon (C), nitrogen (N), C/N ratio, and phosphorus (P) means and standard errors in main-effect and sub-effect treatments measured in six years (2004) and 16 years (2014) after the treatments installed.

Year	Element	Depth (cm)	Main effect treatment					Sub-effect treatment		
			Control	T	T/S	T/F/S	T/C/S/R	T/S/C	T/C/F/S/R	T/S/C/F
2004	C (Mg ha^{-1})	0–10	21.8 (2.3)	23.8 (1.0)	21.1 (1.3)	23.1 (1.4)	20.4 (1.5)	20.9 (0.5)	23.5 (1.0)	28.5 (1.8)
		10–20	15.8 (0.9)	15.7 (0.7)	17.3 (0.8)	17.2 (1.4)	16.2 (1.1)	16.1 (0.9)	20.0 (2.1)	18.8 (1.2)
		20–30	15.2 (1.8)	14.8 (1.5)	14.5 (0.5)	16.7 (1.5)	16.4 (3.4)	12.1 (1.9)	16.1 (1.4)	14.4 (1.7)
	N (Mg ha^{-1})	0–10	1.34 (0.07)	1.39 (0.04)	1.29 (0.05)	1.38 (0.06)	1.27 (0.10)	1.28 (0.04)	1.39 (0.03)	1.63 (0.09)
		10–20	1.12 (0.03)	1.16 (0.04)	1.15 (0.04)	1.20 (0.04)	1.11 (0.03)	1.09 (0.04)	1.30 (0.05)	1.20 (0.05)
		20–30	1.05 (0.06)	1.09 (0.04)	1.08 (0.02)	1.13 (0.05)	1.10 (0.07)	0.95 (0.06)	1.12 (0.03)	1.08 (0.04)
	C/N	0–10	16.2 (1.0)	17.2 (0.8)	16.4 (0.5)	16.6 (0.4)	16.3 (1.1)	16.4 (0.3)	16.9 (0.9)	17.5 (0.7)
		10–20	14.1 (0.7)	13.6 (0.3)	15.0 (0.3)	14.1 (0.8)	14.6 (1.3)	14.8 (0.6)	15.3 (1.3)	15.4 (0.4)
		20–30	14.4 (1.1)	13.4 (0.9)	13.5 (0.5)	14.7 (1.1)	14.6 (2.0)	12.5 (1.2)	14.3 (1.1)	13.2 (1.1)
	P (Mg ha^{-1})	0–10	15.5 (3.3)	14.4 (2.1)	12.4 (1.2)	21.8 (5.0)	13.7 (3.7)	12.7 (2.4)	17.6 (2.5)	17.3 (5.1)
		10–20	14.7 (2.6)	11.9 (1.9)	11.8 (1.4)	18.6 (2.2)	14.0 (4.5)	9.7 (4.5)	16.4 (3.5)	14.7 (2.8)
		20–30	14.4 (1.8)	13.2 (1.9)	16.0 (1.5)	21.9 (4.5)	11.2 (1.3)	19.4 (7.1)	20.8 (3.8)	12.8 (1.8)
2014	C (Mg ha^{-1})	0–10	27.7 (5.0)	23.6 (2.4)	22.4 (1.3)	29.6 (4.7)	22.9 (3.1)	34.2 (4.0)	27.7 (4.6)	29.5 (4.9)
		10–20	16.9 (1.6)	19.0 (1.9)	17.3 (1.8)	18.2 (1.8)	19.8 (3.3)	18.4 (2.2)	19.7 (2.5)	23.6 (3.2)
		20–30	10.9 (1.1)	13.2 (2.1)	10.7 (0.8)	11.6 (1.0)	15.8 (4.0)	17.3 (4.2)	19.3 (3.4)	18.6 (3.5)
	N (Mg ha^{-1})	0–10	1.27 (0.16)	1.13 (0.08)	1.09 (0.04)	1.34 (0.16)	1.17 (0.18)	1.38 (0.17)	1.34 (0.15)	1.36 (0.14)
		10–20	0.97 (0.07)	0.95 (0.06)	0.97 (0.07)	1.04 (0.08)	1.06 (0.18)	0.98 (0.06)	1.05 (0.11)	1.22 (0.10)
		20–30	0.73 (0.08)	0.81 (0.07)	0.79 (0.04)	0.85 (0.06)	0.79 (0.10)	0.90 (0.09)	0.92 (0.06)	1.00 (0.09)
	C/N	0–10	21.7 (2.5)	20.5 (0.9)	20.7 (0.9)	21.7 (1.0)	19.7 (0.7)	24.9 (0.8)	20.4 (1.6)	21.2 (1.5)
		10–20	17.8 (2.5)	19.7 (1.3)	17.6 (1.1)	17.4 (0.6)	18.7 (0.5)	18.7 (1.6)	18.8 (1.9)	19.3 (1.3)
		20–30	15.0 (0.7)	15.7 (1.6)	13.3 (0.5)	13.8 (0.5)	19.7 (3.6)	19.2 (4.5)	20.9 (3.6)	18.2 (2.0)
	P (Mg ha^{-1})	0–10	12.3 (1.4)	10.3 (0.9)	9.9 (0.8)	22.1 (5.1)	9.8 (1.7)	10.1 (1.3)	36.8 (9.7)	17.2 (5.3)
		10–20	11.0 (1.3)	9.8 (0.6)	10.5 (0.8)	11.2 (1.5)	12.3 (2.3)	9.8 (3.2)	36.2 (13.1)	10.5 (1.0)
		20–30	12.1 (2.6)	9.9 (1.2)	10.2 (1.2)	10.2 (1.0)	10.4 (1.6)	10.1 (1.7)	15.2 (2.6)	13.0 (1.3)

T = thin; S = sub-soiling; F = fertilization with N and P; C = chips returned; R = rototilled.

4.2% in control, T, T/S, and T/F/S main treatments, respectively, over the ten years. However, sub-effect treatments showed much higher C accumulation with 10.4%, 42.4%, 11.9%, and 16.2% increase in T/C/S/R, T/S/C, T/C/F/S/R, and T/S/C/F respectively.

4. Discussion

4.1. Thinning and soil compaction

Soil bulk density measured six years after initial treatments were applied showed that mechanical thinning operations did not compact the soils (Table 2). More importantly, no significant differences in D_{bt} and D_{bf} were detected on traffic lanes versus non-traffic lanes (adjacent "undisturbed" rows). These results differ from the penetrometer readings taken shortly after treatments were applied in the fall of 1998 (Fig. 4), in which Powers et al. (1999) found that soils were compacted by mechanized thinning operations and loosened by subsoiling. Their results showed that soil strengths increased by approximately 1 MPa at all measured depths beneath traffic lanes (Fig. 4A). Subsoiling tillage loosened the soil to or beyond original conditions (Fig. 4B). The discrepancy between methods appears to be that bulk density is not as sensitive as strength measurement to compaction (Moghaddas and Stephens, 2008; Picchio et al., 2012). By thinning 64% of stems in a 33-year-old *Pinus nigra* plantation, Picchio et al. (2012) found that thinning changed soil properties – penetration resistance of soil increased by about 50% and shear resistance by almost 40%. But bulk density and porosity did not change significantly. Another possibility was that the compacted soil could have naturally recovered within six years, although this was less likely because compacted soil is often found to take a long time to naturally recover (Cambi et al., 2015; Froehlich et al., 1985; Greacen and Sands, 1980; Page-Dumroese et al., 2010b).

Although soil compaction has been reported as a common problem in stand-removal harvest operations, thinning-related impacts may vary due to different traffic patterns (Powers et al., 1990; Miller and Anderson, 2002; McIver et al., 2003). By reviewing the literature on impacts of thinning harvests in the western United States, Page-Dumroese et al. (2010b) concluded that thinning operations are less likely to cause significant soil compaction than with a stand-removal harvest, although the impacts of mechanical operations on soil physical properties depends on many factors such as harvesting methods, wood debris on the traffic lanes, machinery types and operation techniques, soil texture, soil condition and properties, and possibly other factors. In this study, the thinning operation was carefully conducted on young plantations with a soil type having relatively high bulk density. Also, the harvester and skidder used here had large balloon-type tires, with lower psi than many conventional skidders, and was handling pre-commercial trees so payloads were relatively light. Therefore, the impact of thinning was expected to be small. Similar results were also found in previous studies. For example, King and Haines (1979) reported an absence of soil compaction in *Pinus elliottii* plantation thinning in Alabama. York et al. (2015) found that thinning treatments had minimal effect on soil compaction in mixed-conifer plantations in the Sierra Nevada, California. Even in fuels treatment thinnings in natural stands or plantations, significant soil compaction was not found for a range of soil types and different forests (Stephens et al., 2012). Hatchett et al. (2006) found that mastication appears to be an effective thinning treatment for overstocked forests with few discernible negative impacts including soil compaction. Moghaddas and Stephens (2008) suggest that the lack of soil compaction was due to the debris bed which thinning and/or mastication operations created.

4.2. Thinning and tree growth

Thinning increases diameter growth and maintains crown lengths for residual trees, which has been confirmed over a century of research (cf. Assmann, 1970). In this study, the thinned plots

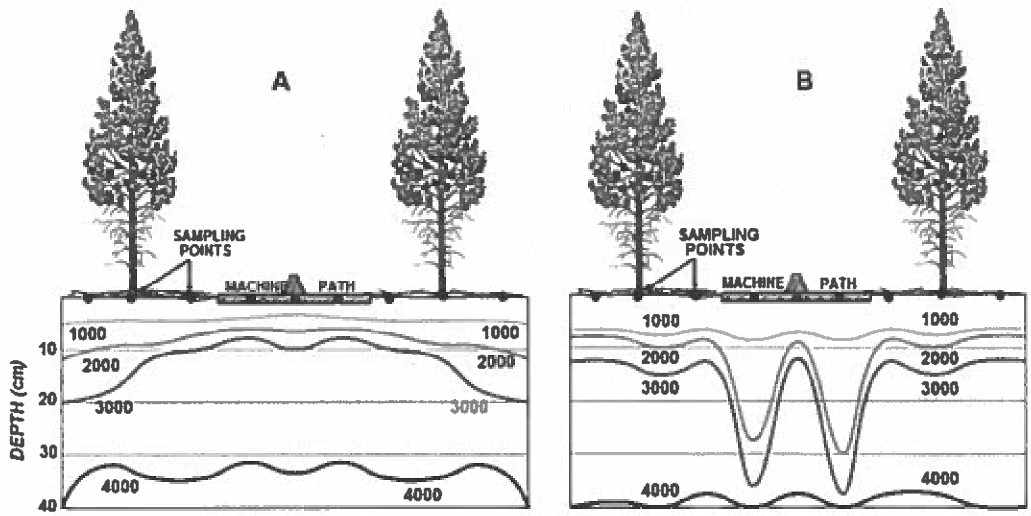

Fig. 4. Soil strength (MPa) isolines measured in fall 1998 following mechanized thinning. (A) Thinned only. (B) Thinned and tilled along harvester tracks. This is redrawn from Powers et al. (1999).

increased in diameter and height growth for 15 years (Fig. 2A and C). Because thinning was intense, taking out 2/3 of the trees, it decreased basal area and volume yield per unit area as a result of the sharp decrease in stem density (Fig. 2E–H). Usually, at high density or with light thinning, long-term net basal area growth and volume yield tends to be low because of mortality from competition or bark beetles (Zhang et al., 2013a, 2013c). Surprisingly, heavy mortality did not occur even though stand density index was close to 1000 trees ha^{-1} in the control plots (data not shown). This number was close to or beyond the self-thinning line found for ponderosa pine even-aged stands in northern California and southern Oregon (Oliver, 1995; Zhang et al., 2013b).

The lack of statistically significant difference in stem BA growth in the second growing period and volume growth between thinned plots and plots mitigated with subsoiling indicate that residual trees did not respond negatively to any compaction caused by thinning, regardless if the compaction was significant or not (Fig. 2A, C, E, and G). We offer several explanations. First, soils were either not compacted much at all, as our bulk density measurements indicated (Table 2), or soils were compacted (Fig. 4), but below a threshold that hindered tree growth (cf. Greacen and Sands, 1980; Binkley and Fisher, 2013). Second, the subsoiling that was supposed to mitigate the compaction problem damaged one side of live tree roots, which may have stressed the remaining trees, as seen by Hogervorst (1994) and Otrosina et al. (1996). Lastly, while compaction can cause substantial reduction of tree growth in certain situations, it may fail to have impact on growth in other circumstances (Ampoorter et al., 2011; Gomez et al., 2002; Ponder et al., 2012). Growth responses to soil compaction have been negative on silty or fine-textured soils (Froehlich et al., 1986; Scott et al., 2014; Powers et al., 2005). Many studies conversely found that compaction of coarse-textured soils reduced macropore space and subsequently increased soil water holding capacity, and therefore improved tree growth (Gomez et al., 2002; Powers et al., 2005). In the current study, lack of treatment effect on growth (except for the controls) might have resulted from the interactions among imposed treatments such as subsoiling, fertilization, rototilling, and insect damage.

4.3. Thinning, subsoiling, and insect damage

Although we did not find heavy mortality in the control plots, percent of insect damage, mainly by red turpentine beetles, was unexpectedly higher in the treated plots than in the control plots (Fig. 3A). As a result, mortality was also substantially lower in the control plots (Fig. 3C). The treatments were applied in association with a lot of other thinning in the surrounding plantations across the Pondosa Fire area during the same time period. The thinning was started in the spring even though the treatments in this study, including sub-soiling, were installed in July. The subsoiling resulted in severing of root systems along tillage lines. The operations predisposed trees to possible beetle attack (Owen et al., 2010), as also found in thinning in *Pinus taeda* (Nebeker and Hodges, 1983). Owen et al. (2010) found that red turpentine beetle killed pole-size, drought-stressed ponderosa pine following thinning or thinning plus subsoiling conducted in the spring, just before or during peak flight at the study area. Nonetheless, our data here could not separate whether beetle damage was caused by thinning, subsoiling root damage, or both. Regardless, thinning and post-thinning operations should prudently avoid pine dominated forests or plantations during the peak period of beetle flight.

4.4. Nutrient status and tree growth

The purposes of fertilization were to re-supply nutrients removed during thinning and whole-tree harvesting, and lower the C/N ratio to favor microbial decomposition. The results indicated that the fertilization significantly increased tree diameter and height increment in the main-effect plots (Fig. 2A and C) and only PAI QMD in the sub-effect plots (Fig. 2B) during the first five years. The fertilizer effect was positive but non-significant at all other growth measurements during the period of the study. The results differed from some previous studies in ponderosa pine plantations. Powers et al. (1988) reported that volume of ponderosa pine increased linearly with fertilization rate through 356 kg ha^{-1} of N; the magnitude varied with thinning spacing, with average increase around 30%. Substantial volume increase was also found in young ponderosa pine plantations in northern California by Wei et al. (2014), although these trees were fertilized four times. Repeated fertilization regimes were recommended to enhance growth of pine plantations (Brockley, 2010).

The lack of a significant fertilizer effect for basal area and volume in general, especially during 5–15 years after treatments (Fig. 2), is unexpected. To search for possible explanations, we compared fertilized plots with unfertilized plots to determine if the 244 kg ha^{-1} N and 336 kg ha^{-1} P were sufficient to observe changes in soils. Clearly, our results showed that N and P were higher in main treatment T/F/S than in T/S at all depths, at both 6 and 16 years after treatments (Table 3). Similar trends were also found when T/C/F/S/R and T/S/C/F were compared to T/C/S/R/ and T/S/C in the sub-treatment plots. Therefore, added fertilizers entered into the systems and did elevate soil nutrient status.

One possibility might be that thinning increased availability of N and P for the residual trees, so that a fertilization effect was not detected (Smethurst and Nambiar, 1990). Our results showed this in comparing total amount of N and P in controls versus non-fertilized thinning treatments (Table 3). In fact, stand response to thinning and fertilization appears to depend on the initial nutrient pool and other soil physical and climatic factors (Grier et al., 1989; Miller, 1981).

Another explanation for the lack of fertilization effect could have been a shortage of soil water (Powers and Jackson, 1978; Powers and Reynolds, 1999). During the 15 years after treatments, several pronounced periods of drought occurred in this vicinity, exacerbating a rain-shadow effect of Mt. Shasta to the west. Also, harvest operations reduce or eliminate soil organic cover in traffic lanes, exposing the soil to higher temperatures and higher evaporative losses of soil moisture for at least several years. If trees have insufficient soil water during the growing season to produce tissues, they cannot take advantage of additional soil nutrients.

There is one caveat, although positive fertilizer effect was not statistically significant, an increase of 5–27% in basal area or volume growth can be important if these young plantations cover a huge land base resulting from the post-wildfire regeneration programs in California and western United States. The lack of statistical significance in growth differences could simply have been due to small sample size, lack of fertilizer application for non-thinned stand, and/or a combination of high variability and modest gains at a single site.

4.5. Chip returns and N, P, C pools

A major concern for thinning or biomass removal is the possibility of reducing site productivity by depleting the nutrient pools with whole tree removals (Powers, 2012). The objectives of chip returns to the site were to see if residue retention would improve soil fertility. The chips were either retained on the surface to act as a mulch or tilled into the surface soil to increase decomposition and eventually soil organic matter. The results from this study showed a slight N amelioration with chip returns 16 years later, but not P unless fertilization was applied, as seen for P measured in both 6 years and 16 years after the treatments (Table 3). Surprisingly, C/N ratio was not affected by N fertilization. The reason for this might be due to the chip returns in the sub-effect treatments, but was unclear in the main effect T/F/S. Perhaps, supplemental N had entered the crown nutrient pools immediately after the treatments because of high demands of residual trees for nitrogen to build up crowns (Brix, 1983); C/N ratios did not differ significantly among main-effect treatments.

Carbon storage in the top 30 cm of soils was more than 49 Mg ha^{-1} in these 20-year-old plots in 2004. Although 67% of the trees were thinned 6 years prior, total soil C in the treatments was not significantly different from controls, although C trended higher in all the treatments except for T/S/C (Table 3). The C sequestration in upper 30 cm soils from 2004 to 2014 was much higher in the sub-effect treatments with the chip returns (⩾10.4%) than in the main effect treatments without the chip returns (⩽5.1%). Within the sub-effect treatments, rototilling (T/C/S/R and T/C/F/S/R) showed lower C sequestration by comparing increases between 2004 and 2014 with 10.4% for T/C/S/R, 11.9% for T/C/F/S/R, 42.4% for T/S/C, and 16.2% for T/S/C/F, respectively. Sixteen years after treatments, the control plots held 55.5 Mg ha^{-1} in the top 30 cm of soils, while the T/S/C/F treatment contained 71.7 Mg ha^{-1}. Except for T/S, which showed negative C sequestration, the two other main-effect treatments showed less percentage C increases than controls (2.8% for T, 4.2% for T/F/S, 5.1% for Control). The four sub-effect treatments showed 10.4–42.4% increases from 2004 to 2014. The ten-year increments and the total soil C were less than what were reported on Long-Term Soil Productivity field sites with ponderosa pine as the dominant species, but were comparable with the numbers at other sites with pure ponderosa pine (Powers et al., 2013), especially with similar site index (McFarlane et al., 2009).

5. Conclusions

Several conclusions can be reached based on results of this study. (1) Thinning operations did not compact soils that are similar in soil texture to the current study site, at least, not enough to affect growth rate of residual trees. (2) Neither subsoiling nor rototilling, both of which might mitigate soil compaction, enhanced tree growth in this thinning operation. (3) Short-term plantation growth was not improved by chip returns and chips with fertilization, this result being attributed to sufficient initial nutrient capital at this site, and possibly soil moisture being the limiting factor. (4) Any management operations that involve cutting or damaging trees should be avoided during active periods of bark beetle flight. (5) Thinning and other post-thinning treatments did not reduce the carbon sequestration in the mineral soils, while chip returns enhanced it. We conclude that when best practices are used by forest managers in a similar forest and site setting, thinning operations will not compact the soils with a detrimental effect on tree growth; thus compaction mitigation treatments were not warranted. Lack of growth benefits from chip returns, rototilling, and direct fertilization for a longer period was unexpected and appeals to further investigation.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.foreco.2016.03.021. These data include Google maps of the most important areas described in this article.

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