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Aboveground biomass responses to organic matter removal, soil compaction, and competing vegetation control on 20-year mixed conifer plantations in California

Jianwei Zhang [a,*], Matt D. Busse [a], David H. Young [b], Gary O. Fiddler [b], Joseph W. Sherlock [c], Jeff D. TenPas [c]

[a] USDA Forest Service, Pacific Southwest Research Station, 3644 Avtech Parkway, Redding, CA 96002, USA
[b] USDA Forest Service, Pacific Southwest Region, 3644 Avtech Parkway, Redding, CA 96002, USA
[c] USDA Forest Service, Pacific Southwest Region, 1323 Club Drive, Vallejo, CA 94592, USA

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ABSTRACT

We measured vegetation growth 5, 10, and 20 years following plantation establishment at 12 Long-Term Soil Productivity installations in California's Sierra Nevada and Southern Cascades. The combined effects of soil compaction (none, moderate, severe), organic matter removal (tree bole only, whole tree, whole tree plus forest floor), and competing vegetation control (complete: VC, none: NVC) on aboveground biomass were tested. Soils ranged from sandy loams to clay loams and were compacted (10–25% bulk density increase) prior to planting of mixed-conifer seedlings. Soil compaction resulted in a 15% increase in planted tree biomass on a plot-scale basis, attributed to improved seedling survival, along with reduced competing vegetation biomass on NVC plots. The unexpected response of tree growth to compaction was consistent across the LTSP sites. After year 5, there were no differences among the diverse organic matter treatments in tree biomass, periodic annual increment, or competing vegetation biomass. In contrast, vegetation control had a strong positive effect on tree biomass, about 68% greater tree growth (129.13 Mg ha^{-1}) compared to trees grown on NVC plots (76.83 Mg ha^{-1}). However, total vegetation biomass (trees + competing vegetation) was greater without vegetation control for the initial 10 years of the study, prior to canopy closure. The results showed near-complete tolerance by forest biomass to soil compaction and surface organic matter manipulation on LTSP plantations across a wide geographic range in California. Vegetation control was the single most important factor affecting 20-year tree biomass.

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1. Introduction

Thinning and timber harvesting unavoidably disturb soils. Of particular concern are the effects of mechanized equipment on soil physical integrity, and the removal of harvest materials and nutrients therein on soil fertility. The North American Long-Term Soil Productivity (LTSP) program was established in response to these concerns (Powers et al., 1989, Powers, 2006). Manipulative treatments of organic matter removal and soil compaction were achieved during timber harvesting and site preparation for new plantations. Competing vegetation control was applied after trees were planted. Four null hypotheses were: "(1) Pulse changes in site organic matter and (or) soil porosity do not affect the sustained productive potential of a site. (2) If impacts on productivity occur from changes in organic matter and porosity, they are universal regardless of climate and soil type. (3) If impacts do occur, they are irreversible. (4) Plant diversity has no impact on the productive potential of a site" (Powers, 2006). These principles have guided the LTSP program for more than two decades.

Soil compaction with ground-based equipment has been extensively studied and reviewed (Ampoorter et al., 2011; Greacen and Sands, 1980; Cambi et al., 2015). Changes in soil bulk density or porosity are typically measurable and negative, although the extent and degree of compaction depends on soil texture, moisture, organic matter content, slope of the terrain, and type of harvesting equipment (Cambi et al., 2015; Froehlich et al., 1985; Reeves et al., 2012; Sands et al., 1979; Tiarks and Haywood, 1996; Vora, 1988). As a consequence, the response of tree productivity has varied from positive (Gomez et al., 2002), to neutral (Miller et al., 2010; Holub et al., 2013; Zhang et al., 2016b), to negative (Geist et al., 2008; Murphy et al., 2004). Early results prior to age ten from the LTSP sites found that compaction either had no effect, or increased plot-level tree biomass accumulation because the prac-

* Corresponding author.
E-mail address: jianweizhang@fs.fed.us (J. Zhang).

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tice ameliorated seedling survival or increased soil water-holding capacity (Fleming et al., 2006; Powers et al., 2005; Ponder et al., 2012). At the individual tree level, Gomez et al. (2002) reported both growth enhancement and reductions due to compaction on stem volume among three sites with varied ages from 3 to 8, which appeared to relate to soil type and various topographic characteristics, although the tree stocking density was not considered.

When trees are harvested from a plantation or a natural stand, a significant amount of nutrients can be removed, particularly in crown foliage. However, a meta-analysis of 749 case studies by Achat et al. (2015) found that whole-tree harvest reduced subsequent tree growth by only 3–7% compared to stem-only harvest. Indeed, the first ten-year results from the LTSP study failed to detect a significant impact of whole-tree removal on growth of young plantations (Fleming et al., 2006; Powers et al., 2005; Ponder et al., 2012). At Louisiana and Texas LTSP sites, even whole tree harvesting plus forest floor removal did not affect tree growth at age 15 (Scott et al., 2014). After reviewing literature across temperate and boreal forests, Thiffault et al. (2011) found a lack of consistent, unequivocal effects of forest biomass harvesting on soil productivity. Biomass harvesting can influence seedling survival and growth, either positively or negatively, through its effects on microclimate and competing vegetation (Proe et al., 1999).

Control of competing vegetation has a universal positive effect on tree growth of plantations (Zhang et al., 2013a). However, the *magnitude* of the effect appears to vary with competing vegetation type, site quality and conditions, climate regime, and plantation developmental stage (Zhang et al., 2013a, 2016a). Previous analysis of LTSP data demonstrated that vegetation control consistently enhanced tree biomass regardless of climate or forest type (Ponder et al., 2012). It also increased the total aboveground vegetation (tree + competing vegetation) biomass on sites without abundant competing species, but decreased total biomass on shrub-dominated sites.

As a part of the LTSP program, the Forest Service in California established 12 sites in mixed conifer forests across a diverse range of climate and soil types in the Sierra Nevada and Southern Cascades regions. Although early biomass results from California sites have been reported in a broader perspective with other sites across the USA and Canada (Fleming et al., 2006; Ponder et al., 2012; Powers et al., 2005; Gomez et al., 2002), results at year 20 have not been independently reported in detail. This longer stand development period will provide valuable information in managing these and similar forests.

The purpose of this report is to determine how site productivity is affected by pulse changes in soil porosity and site organic matter manipulations, one of the four main objectives of the LTSP program. In addition, we examine how the control of competing vegetation interacts with the effects of compaction and organic matter removal on aboveground biomass, and further determine whether any treatment effects on biomass have changed with stand development.

Three hypotheses tested are: (1) soil compaction will negatively affect both aboveground biomass of planted trees by themselves and aboveground biomass of total vegetation (trees + competing vegetation), and the trends will be consistent at 5, 10, and 20 years of plantation growth; (2) both whole-tree harvest and whole-tree plus forest floor removal will reduce plantation biomass compared to the stem-only harvest, and the effect will be stronger as the stands age; (3) vegetation control will increase tree biomass prior to an onset of self-thinning or artificial thinning, have no effect on soil compaction response, and modify the effect of organic matter removal due to imposed changes in nutrient availability and uptake by competing vegetation.

2. Materials and methods

2.1. Study site

The California LTSP installations were established at 12 forested sites with three at the southern end of the Cascades and nine in the Sierra Nevada from 1990 to 1998 (Fig. 1; Table 1). One fortuitous advantage of installing them over eight years is minimizing a bias effect of year-to-year variation. These sites occupy a diverse geographic region covering 3.5 degrees of latitude, 2 degrees of longitude, and 170 m of elevational gradient. Site index ranges from 14 m to 30 m at age 50. This region has a Mediterranean climate characterized by hot and dry summers and cold and wet winters, which varies a great deal among the sites, including a 5 °C range in mean annual temperature and a 1200 mm range in annual precipitation. Approximately 90% of precipitation occurs between November and April, with a significant portion as snow on most sites.

All sites represented an array of the major soil types found in northern California (Table 1), and prospective plots were carefully examined for variation in soil and stocking. All sites had mature mixed conifer natural stands, and had little or no previous management history or disturbance other than historic fires. At establishment, forest stands were inventoried and at least 30 trees per installation were felled and sampled to estimate the biomass and nutrient contents of their boles and crowns (Powers and Fiddler, 1997). The understory (mainly shrubs of *Arctostaphylos* and *Ceanothus spp* ranging from a few centimeters to two meters tall), forest floor (all organic detritus above the mineral soil), and mineral soil were also sampled for mass and nutrient content. Regression methods were used to expand sample data to a unit-area basis.

2.2. Treatment design

Once sites were characterized, all trees were removed by equipment outside the plots or full-suspension cable to avoid compaction. Then, nine factorial treatments (three levels of organic matter removal by three levels of soil compaction) were assigned randomly to 0.4-ha plots. Only five of the nine plots were installed at Vista due to more extreme site variability.

Site organic matter (OM) was treated by (i) removing tree boles only; lopped and scattered crowns, felled understory, and forest floor organics were retained (OM0), (ii) removing all aboveground living vegetation; forest floor organics were retained (OM1), (iii) manually removing all surface organic matter to expose bare soil; no organic matter was retained (OM2). ***Soil compaction*** (C) treatments included (i) no soil compaction (C0), (ii) compacting to an intermediate bulk density (C1), and (iii) compacting to a high bulk density (C2). The study design intended for deliberate, experimental compaction over as near to 100% of the plot area as possible. The compaction treatment was achieved by a combination of vibrating pavement compactors (highway rollers) for most areas and a vibrating plate compactor mounted on a tracked excavator boom for areas around stumps or between closely spaced stumps that the rollers missed. Soils could not be sufficiently compacted when surface organics were retained, so all organic matter including logging debris and forest floor materials was manually removed from the plots and carefully replaced after compacting. Plots were compacted during the spring when soils were moist. Measurements of forest floor and soil physical characteristics will be presented in a separate paper.

Treatment plots were divided into two, 0.2-ha subplots. Competing plant species were allowed to develop naturally on one subplot (NVC). Only planted trees were kept in the other subplot (VC), which was achieved with repeated control treatments for the first

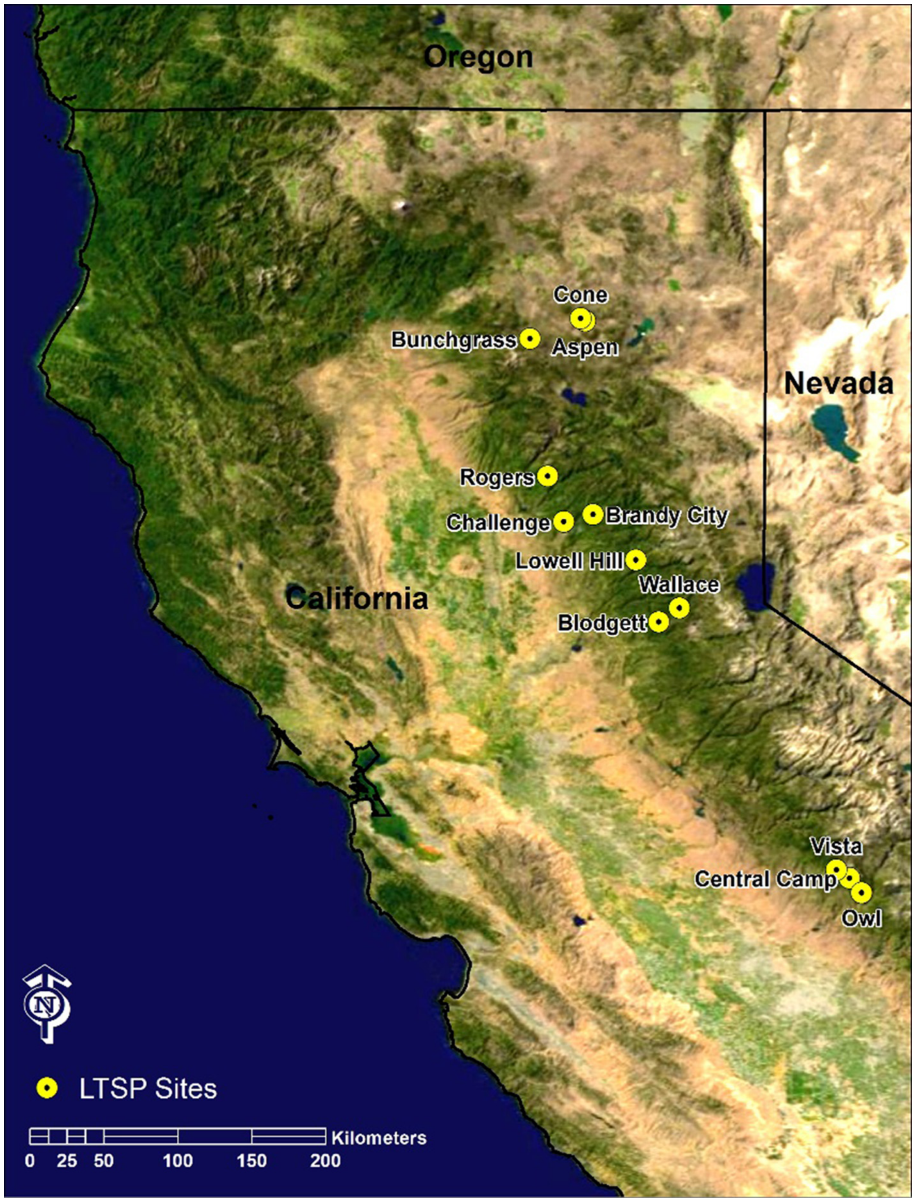

Fig. 1. California Long-Term Soil Productivity (LTSP) installation GIS map.

five years. Six of the sites used herbicide control methods, and the other 6 used manual control methods; one site used both methods with additional plots for comparison. Thus, treatments of site organic matter removals and soil compaction produced a factorial main plot with competing vegetation control or not (VC or NVC) as subplots. Plots were planted with three to five tree species, native to the site: ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson), white fir (*Abies concolor* (Gord. & Glend.) Lindl. ex Hildebr.), sugar pine (*Pinus lambertiana* Douglas), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), and giant sequoia (*Sequoiadendron giganteum* (Lindl.) J. Buchholz). Seedlings were planted in spring using a power auger with 10 cm diameter at 2.4 x 2.4 m spacing with at least one ponderosa pine at each planting spot. Another species was planted next to the ponderosa pine as assigned to that particular species on the planting map. The double seedlings were thinned after 1–2 years, with a seedling of designated species preferably retained. The number of species that were planted at each site is shown in Table 1. A power auger was necessary for planting because compacted plots could not be penetrated by hand planting techniques; the auger was thus used on all plots to a depth of about 20 cm, sufficient for seedling roots but shallower than the compaction depth so as not to negate the compaction treatment.

2.3. Tree measurements

An inner 0.1-ha measurement plot was established in each of the 0.2-ha subplots, and all planted trees were tagged. Diameter at 15 cm height was measured if tree height was less than 2 m and at breast height (dbh, 1.37 m) for trees >2 m at age 5 and 10 for all sites, and age 20 for nine sites (three sites have not yet reached 20 years). Tree height (ht), height to live crowns (hlc), and crown width (cw) in two directions were also measured for all planted trees in these measurement years. With these measurements, we estimated individual-tree biomass using biomass allometric equations developed for northern California conifer forests, or elsewhere if allometric equations were not available for some species (Powers et al., 2013). By summing individual tree data, we obtained stand-level aboveground tree biomass (Mg ha^{-1}). We also calculated individual tree canopy cover (CC)

Table 1
Geographic location, site characteristics, and planted conifer species at California Long-Term Soil Productivity installations.

Location	Est. year	Lat. (°N)	Long. (°W)	Elev. (m)	Slope (deg.)	Aspect	AWS (cm)	Soil texture	Precip. (cm)	T_{air} (°C)	SI (m) at age 50	Planted species				
												ABCO	PIPO	PILA	PSME	SEGI
Aspen	1998	40.71	121.09	1798	4	SE	10.7	Fine SL	67	6.4	14.6	x	x	x		
Blodgett	1994	38.88	120.64	1320	2	W	16.8	L	165	11.3	30	x	x	x	x	x
Brandy City	1995	39.55	121.04	1130	5	NE	23.0	Heavy CL	190	10.9	29	x	x	x	x	x
Bunchgrass	1998	40.59	121.41	1524	2	N	15.5	Coarse SL	91	7.5	14.9	x	x	x		
Central Camp	1993	37.32	119.48	1685	6	W	10.0	Coarse SL	114	9.2	24	x	x	x		x
Challenge	1991	39.48	121.22	790	11	W	25.6	Silty CL	173	13.0	28	x	x	x	x	
Cone	1998	40.73	121.12	1959	6	S	16.1	Fine SL	69	6.2	14.3	x	x	x		
Lowell Hill	1995	39.26	120.78	1270	7	SE	23.0	L	173	11.5	25	x	x	x	x	x
Owl	1993	37.24	119.41	1805	5	SE	13.4	Coarse SL	114	8.7	23	x	x			x
Rogers	1996	39.78	121.32	1200	7	SW	12.5	SL	170	10.2	27	x	x	x	x	
Vista	1993	37.38	119.56	1560	11	E	16.8	Coarse SL	76	9.8	18	x	x	x		x
Wallace	1993	38.97	120.64	1575	2	W	5.9	SL	178	9.6	21	x	x	x		x

AWS: Available Water Storage for the entire soil profile, between 1/3-bar and 15-bar tension (NRCS Web Soil Survey).
Soil texture code: Clay Loam (CL), Loam (L), Sandy Loam (SL).
Species Code: white fir (ABCO), ponderosa pine (PIPO), sugar pine (PILA), Douglas-fir (PSME), and giant sequoia (SEGI).

using $\pi(cw/2)^2$ and crown volume (CrVol) using $\frac{1}{3}(ht\text{-}hlc)\pi(cw/2)^2$. Summation of crown volume is a surrogate measure of canopy closure, integrating information over a segment of the sky hemisphere above one point on the ground (Jennings et al. 1999). Periodic annual increment for aboveground biomass (paiAGB, Mg ha^{-1} yr^{-1}) was calculated by $(B_{t2}-B_{t1})/(t_2-t_1)$ from age 5 to age 10 and from age 10 to age 20, where B is plot-level biomass, t_2 is the current measurement year, and t_1 is the previous measurement year. We did not calculate paiAGB for total vegetation because competing vegetation was not measured for all plots at age 5 and 20.

2.4. Competing vegetation measurements

Aboveground biomass for competing vegetation was sampled at four, 1-m^2 circle plots within NVC subplot buffers for 11 sites at age 5 and all sites at age 10. We sampled four, 2-m^2 circle plots in NVC subplot buffers for nine sites at age 20. We sampled live and dead shrubs separately; we also separated herbaceous species, grass species, and other competing trees including naturally regenerated (unplanted) conifers. As we encountered heavy competitive growth of hardwood species [tanoak (*Lithocarpus densiflorus* (Hook. & Arn.) Rehder), California black oak (*Quercus kelloggii* Newb.), and Pacific madrone (*Arbutus menziesii* Pursh.)] in the NVC subplots at the Challenge site, we instead measured dbh and height for a subsample of these hardwoods and excluded them from the regular competing vegetation plots during the 20-year measurements. Biomass for these hardwoods was estimated from their respective allometric equations (Powers et al., 2013; Jenkins et al., 2004). Within the NVC plots, except as noted, all vegetation was harvested and transported back to the laboratory for processing. Processing included taking air-dry weights, chipping samples into small pieces for a more uniform subsample for biomass and nutrients, recording air-dry subsample weights, oven-drying subsamples at 80 °C to a constant mass, recording dry weights, and extrapolating subsample dry weight back to the whole-sample basis.

2.5. Statistical analysis

All variables were analyzed based on a split-plot, randomized, complete-block design with treatments as the fixed effect and site (regarded as a block) as a random effect using SAS PROC MIXED (SAS Institute Inc., 2012). The statistical model is:

$$y_{ijkl} = \mu + \alpha_i + \beta_j + \alpha\beta_{ij} + \gamma_k + \varepsilon_{1ijk} + \phi_l + \alpha\phi_{il} + \beta\phi_{jl} + \alpha\beta\phi_{ijl} + \varepsilon_{2ijkl}$$

where y_{ijkl} is the dependent variable summarized for the *i*th OM treatment, *j*th compaction (C), and the *k*th site, and *l*th competing vegetation control split, μ is the overall mean, α_i and β_j are the fixed effect of the *i*th OM or *j*th C (i = 1, 2, and 3), ϕ_l is the fixed effect of the l^{th} competing vegetation control (l = 1 and 2), γ_k is the random effect of the *k*th site (j = 1, 2, ..., and 12), $\gamma_k \sim N(0, \sigma_B^2)$, and ε_{1ijk} is an experimental error to test main plot effect and ε_{2ijkl} is for the rest of the terms, $\varepsilon_{1ijk} \sim iid\ N(0, \sigma_{e1}^2)$ and $\varepsilon_{2ijkl} \sim iid\ N(0, \sigma_{e2}^2)$.

For each variable 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. During the model selection process, we selected the model with the minimum Akaike information criterion (AIC). Multiple comparisons among treatments were conducted for least squares means by the Tukey-Kramer test by controlling for the overall $\alpha = 0.05$.

3. Results

3.1. Age 5 biomass response

Fifth-year tree biomass showed a significant treatment effect for both compaction (C) and competing vegetation control (VC) (Table 2). The interaction between OM and C was significant at p = 0.07. Unexpectedly, we found increased tree biomass in compacted plots (1.59 Mg ha^{-1} by averaging C1 and C2) than in non-compacted plots (1.31 Mg ha^{-1}) (Fig. 2A). This increase in growth appears related to a 13% higher survival rate on compacted plots than on non-compacted plots (Fig. 2C) and not to increased growth of individual trees. The OM by C interaction was also related to tree survival in C0 and C1 treatments (Fig. 3A, C). A significant Veg by C interaction for total biomass was related to competing vegetation biomass variation among compaction levels (Fig. 2B). Control of competing vegetation increased tree biomass by 29% (VC 1.68 Mg ha^{-1} versus NVC 1.30 Mg ha^{-1}) (Fig. 2A), while the NVC showed much higher total biomass (4.84 Mg ha^{-1}) than VC plots (1.67 Mg ha^{-1}) (Fig. 2A & B) due to rapid competing vegetation biomass accrual.

The positive compaction effect on tree biomass was clearly demonstrated across site indices regardless of whether competing vegetation was controlled (Fig. 4A–B). Total biomass showed a similar positive trend to compaction (Fig.4c), although it was not statistically significant. Total biomass was higher for OM1 and OM2 than OM0 (Table 2; Fig. 5C). However, the OM effect was

Table 2
Probability (Pr > F) for testing treatment effect for aboveground biomass (log-transformation) of both planted tree and total (trees + competing vegetation) on California LTSP installations at age 5, 10, and 20. Num df and Den df are the numerator and denominator degree of freedom. Age 20 has 3 fewer sites included.

Source of variation	Num df	Age 5				Age 10			Age 20		
		Den df	Tree biomass	Den df	Total biomass	Den df	Tree biomass	Total biomass	Den df	Tree biomass	Total biomass
Organic Matter (OM)	2	75	0.135	54	**<0.001**	84	0.091	0.129	60	0.177	0.835
Compaction (C)	2	75	**<0.001**	54	0.342	84	**0.001**	**0.003**	60	**0.022**	0.482
OM x C	4	75	0.069	54	0.438	84	0.350	**0.005**	60	0.071	0.187
Vegetation Control (Veg)	1	84	**<0.001**	61	**<0.001**	92	**<0.001**	**<0.001**	65	**<0.001**	0.483
Veg x OM	2	84	0.356	61	0.177	92	**0.039**	0.874	65	0.345	0.267
Veg x C	2	84	0.430	61	**0.002**	92	0.475	0.067	65	0.631	0.330
Veg x OM x C	4	84	0.972	61	0.272	92	0.301	0.311	65	0.319	0.361

Bold values refer to significant effects at p < 0.05.

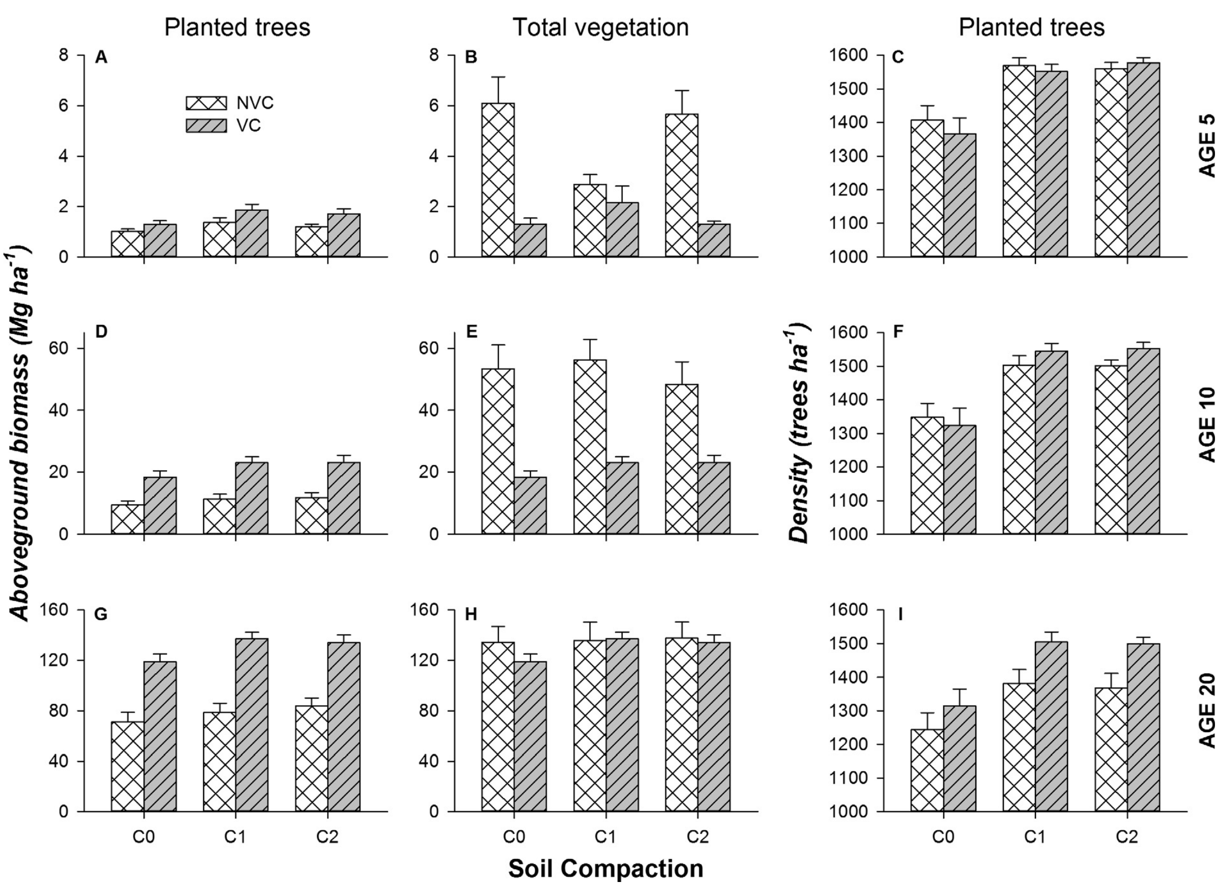

Fig. 2. Vegetation control by soil compaction effects: aboveground biomass measured at NVC and VC subplots for planted trees, total vegetation (trees + competing vegetation), and planted tree density on the California LTSP installations measured at 12 sites at age 5 (A, B, C) and 10 (D, E, F), and 9 sites at age 20 (G, H, I). 5-year total vegetation biomass (B) includes only those plots where competing vegetation biomass was sampled; therefore, biomass in VC was not matched in (A) and in (B). Furthermore, planted tree density (C) is only associated with (A).

nonsignificant for tree biomass for both VC and NVC across the sites, having mixed positive and negative results relative to OM0 across sites (Fig. 5A–B).

3.2. Age 10 biomass response

A significant compaction effect still existed for both tree biomass and total biomass at age 10 (Table 2). There was significantly more tree biomass on VC plots than NVC plots (21.2 versus 10.6 Mg ha^{-1}, respectively), but less total biomass (21.3 versus 52.4 Mg ha^{-1}, respectively) (Fig. 2D–E). Differences in tree density continued to play a significant role for the compaction effect on tree biomass (Fig. 2D–F). Competing vegetation dominated biomass in NVC treatment plots: there was almost four times more biomass in total vegetation than in planted trees (Fig. 2D–E). A significant OM by C interaction for total biomass (Table 2) could not be fully explained by planted tree density (Fig. 3E–F). OM0 had the lowest total biomass in non-compacted plots, yet the highest total biomass in heavily compacted plots.

The main effect of OM effect on tree biomass was nonsignificant at age 10 (Table 2), but there was a significant Veg by OM interaction. With NVC, the trend was OM0 > OM2 > OM1

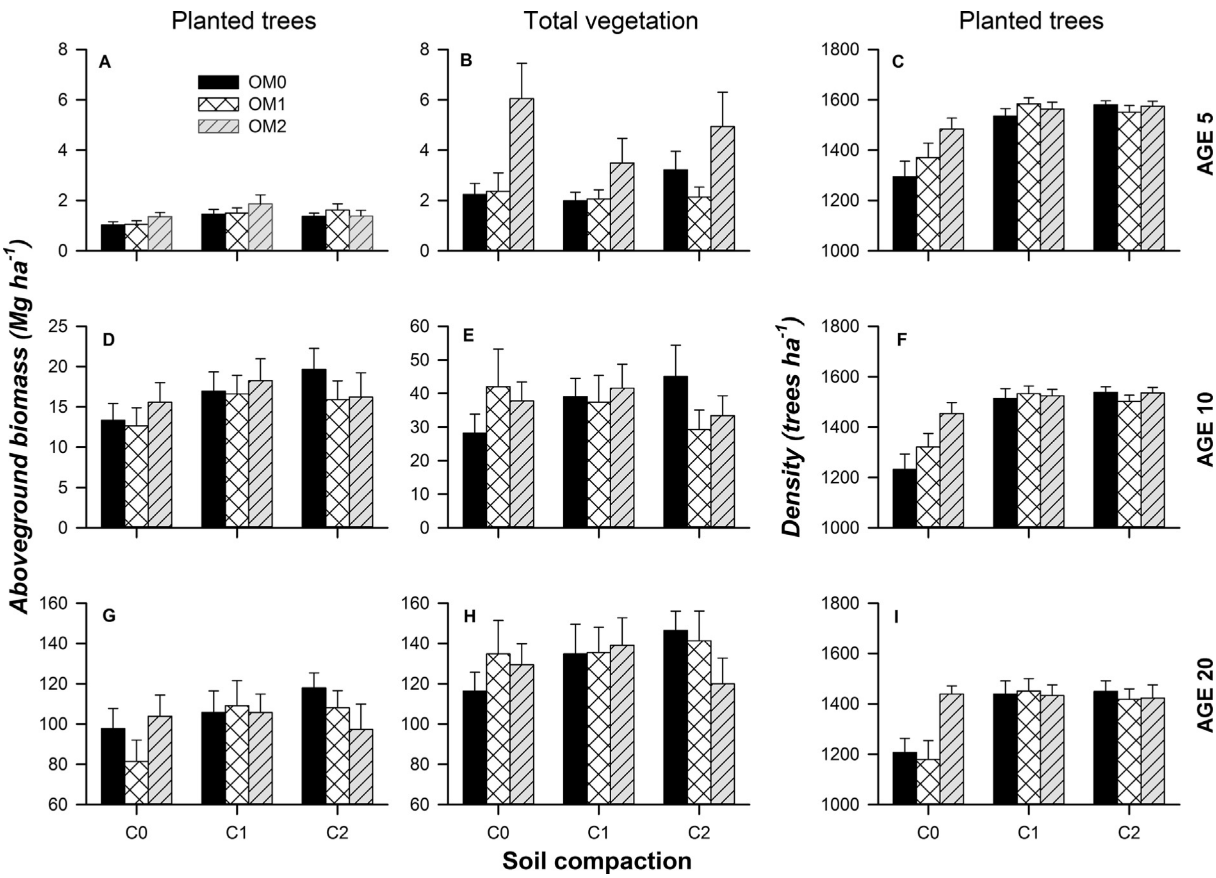

Fig. 3. Organic matter removal by soil compaction effects: aboveground biomass for planted trees and total vegetation and associated planted tree density on the California LTSP installations measured over 12 sites at age 5 (A, B, C) and 10 (D, E, F), and 9 sites at age 20 (G, H, I). Planted tree density (C) is only associated with (A) at age 5 because competing vegetation was not sampled from all treatment combinations.

(11.76 > 10.50 > 10.35 Mg ha^{-1}), which was independent of tree densities of 1419, 1482, and 1447 trees ha^{-1}, respectively (Fig. 6). However, with VC the trend became OM2 > OM0 > OM1 (22.98 > 21.58 > 19.68 Mg ha^{-1}), which was only partially explained by differences in tree density among treatments.

Across the sites as a whole, the positive compaction effect on tree biomass was consistent with previous measurements, regardless of whether or not competing vegetation was controlled (Fig. 4D–E), even though a few of the lower quality sites show slightly negative relative tree biomass with NVC (Fig. 4D). For total biomass, compaction treatments showed reduced biomass relative to C0 at several sites, unlike the trends measured at age 5 (Fig. 4F vs. 4 C). Organic matter removal treatments showed tendencies of negative effects on tree biomass (Fig. 5D–E), although the effect was not statistically significant for both tree biomass and total biomass. A more interesting result is that the negative effects of OM treatments on tree biomass appear more pronounced at sites with lower site index, for both NVC and VC, and there are more negative responses than at age 5 across sites (Fig. 5D–E vs. A–B).

Both paiAGB and crown volume were significantly affected by organic matter removal, soil compaction, and vegetation control at age 10, with no significant interactions found (Table 3). The paiAGB was more than doubled for VC (3.86 Mg ha^{-1} yr^{-1}) than NVC (1.78 Mg ha^{-1} yr^{-1}) (Fig. 7A). About 3.00 Mg ha^{-1} yr^{-1} in the compacted treatments (C1 and C2) was significantly higher than 2.37 Mg ha^{-1} yr^{-1} in the non-compacted soil (Fig. 7D). In the OM treatments, OM1 with 2.48 Mg ha^{-1} yr^{-1} was significantly less than OM0 and OM2 with 3.00 Mg ha^{-1} yr^{-1}. Similar trends were found for the crown volume (Fig. 7C, F). Projected canopy cover (PCC) was significantly affected by compaction, vegetation control, and a Veg∗OM interaction; the OM treatment effect was marginally significant at P = 0.056 (Table 3). Multiple comparisons showed that PCC was significantly greater for VC (0.56 m^2 m^{-2}) than NVC (0.34 m^2 m^{-2}). Similarly, compacted plots (0.46 and 0.49 m^2 m^{-2}) had a significantly greater PCC than non-compacted plots (0.40 m^2 m^{-2}) (Fig. 7E) after averaging VC and NVC for corresponding treatments.

3.3. Age 20 biomass response

Twenty year results showed that compaction and vegetation control significantly affected tree biomass but not total biomass (Table 2). The OM by C interaction for tree biomass was significant at P = 0.071. Vegetation control continued to show significantly more biomass accumulation for planted trees with 129.13 Mg ha^{-1} in the VC and 76.83 Mg ha^{-1} in the NVC by averaging over compaction levels (Fig. 2G). Tree biomass for C1 and C2 treatments (107.55 Mg ha^{-1}) was still greater than the non-compacted treatment (93.83 Mg ha^{-1}) when averaged across vegetation treatments (Fig. 2G). The highest tree biomass in OM2 (103.82 Mg ha^{-1}) was related to the highest tree density (1439 trees ha^{-1}) after moderate mortality occurred in all plots (Fig. 3G). For C2, tree biomass was considerably lower in OM2 (100.15 Mg ha^{-1}) than in either OM1 (106.52 Mg ha^{-1}) or OM0 (120.14 Mg ha^{-1}) despite similar tree density of 1433, 1412, and 1456 trees ha^{-1} in OM2, OM1, and OM0, respectively. None of the treatment effects or interactions were significant for total biomass (Table 2).

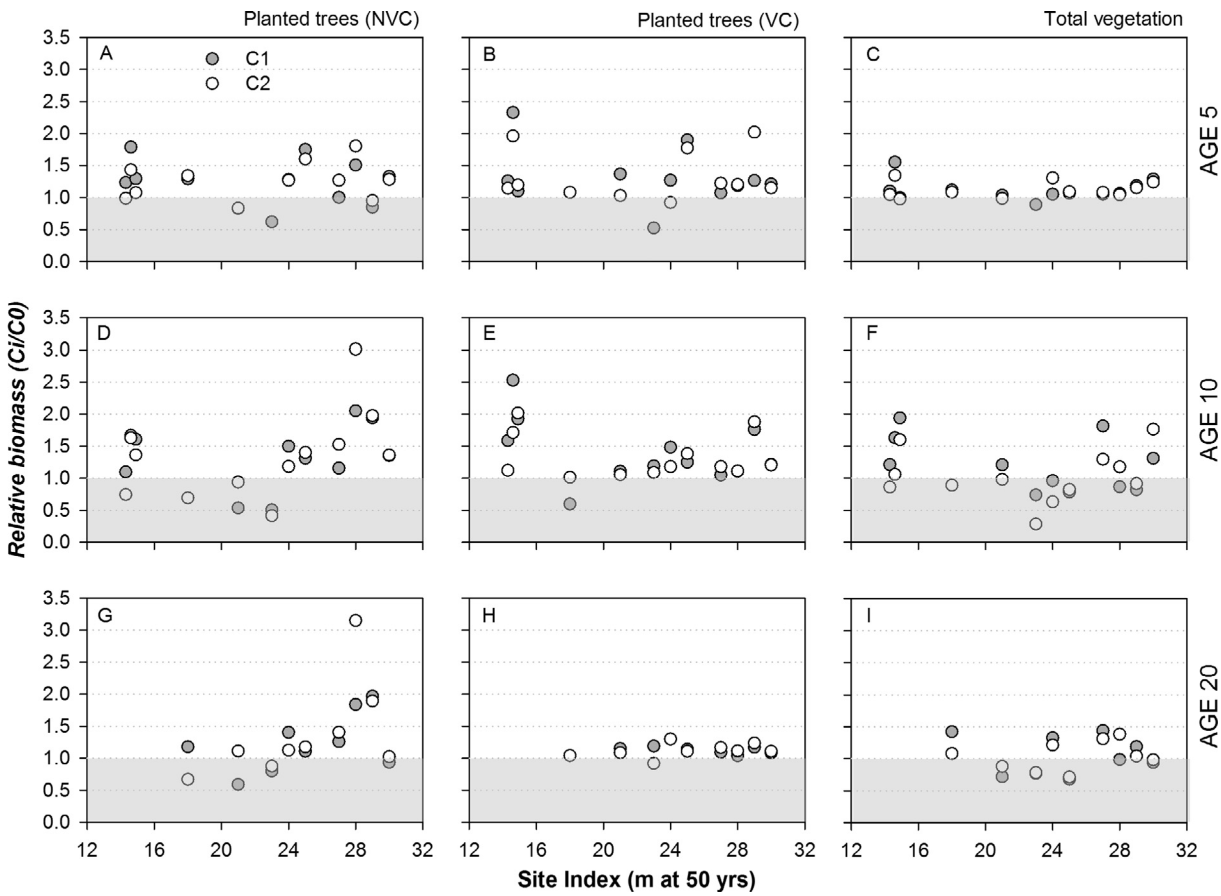

Fig. 4. Relative biomass of both compacted treatments (C1 and C2) to non-compacted treatment (C0) for tree biomass with and without competing vegetation control (VC, NVC respectively), and for total vegetation biomass (trees + competing vegetation) on the California LTSP installations varying with site index at age 5, 10, and 20. The 3 lowest-index sites have not been measured at age 20.

The trends for both compaction and organic matter treatment effects vary similarly as previous years across sites with varying site index (Fig. 4G–I and Fig. 5G–I). The positive effect of compaction continued from the previous years, although on balance the net positive response for planted trees with VC are converging toward a net no-effect (Fig. 4H), excluding the lowest-index sites. Surprisingly, the OM effect moved from the net-negative side to the net-positive side, again excluding the lowest-index sites. It will be interesting to see the trends of aboveground biomass for the three lower quality sites in the Southern Cascades region when they reach 20 years of age (2017).

Effects of compaction and vegetation control were significant for paiAGB, crown volume, and PCC (Table 3). None of the other terms including interactions were significant. Control of competing vegetation increased paiAGB by 77%, crown volume by 66%, and PCC by 39% (Fig. 7G–I), despite the time lapse since any vegetation control treatments have been actively implemented.

3.4. Planted tree biomass dynamics along stand development

Relationships between tree biomass and crown volume were significantly linear and positive, while relationships between tree biomass and canopy cover were non-linear at age 10 and 20, respectively (Fig. 8). These relationships were stronger at age 10 than at age 20. When crown development reached a certain level, biomass has declined in some plots due to tree mortality (Fig. 8D).

3.5. Planted species contribution to tree biomass

Ponderosa pine was the most populated species at age 20, accounting for 55% of tree density and 67% of tree biomass for NVC, versus 52% tree density and 65% tree biomass for VC (Table 4). At the opposite end, white fir accounted for 8.5% of tree density and 1.7% tree biomass for both NVC and VC. Regardless of VC or NVC, giant sequoia accounted for 16% of tree density and 22% of tree biomass; sugar pine accounted for 8.5% of density and 3% of tree biomass; and Douglas-fir accounted for 14% of tree density and less than 7% of tree biomass. These relationships, site by site, will be further investigated in a follow-up report.

4. Discussion

4.1. Soil compaction

A significant positive effect on tree biomass and lack of consistent effect on total vegetation biomass from soil compaction treatments at these installations at age 5, 10, and 20 lead us to reject our first hypothesis. The trends are consistent with what has been reported in the previous regional comparison of LTSP sites at younger ages (Fleming et al., 2006; Ponder et al., 2012; Powers et al., 2005). There was more tree biomass in the compacted plots than in the non-compacted plots (Table 2; Fig. 2A, D, G). This trend was caused by the survival rate of planted trees (Fig. 2C, F, I). When the tree biomass data were analyzed using density as a covariate,

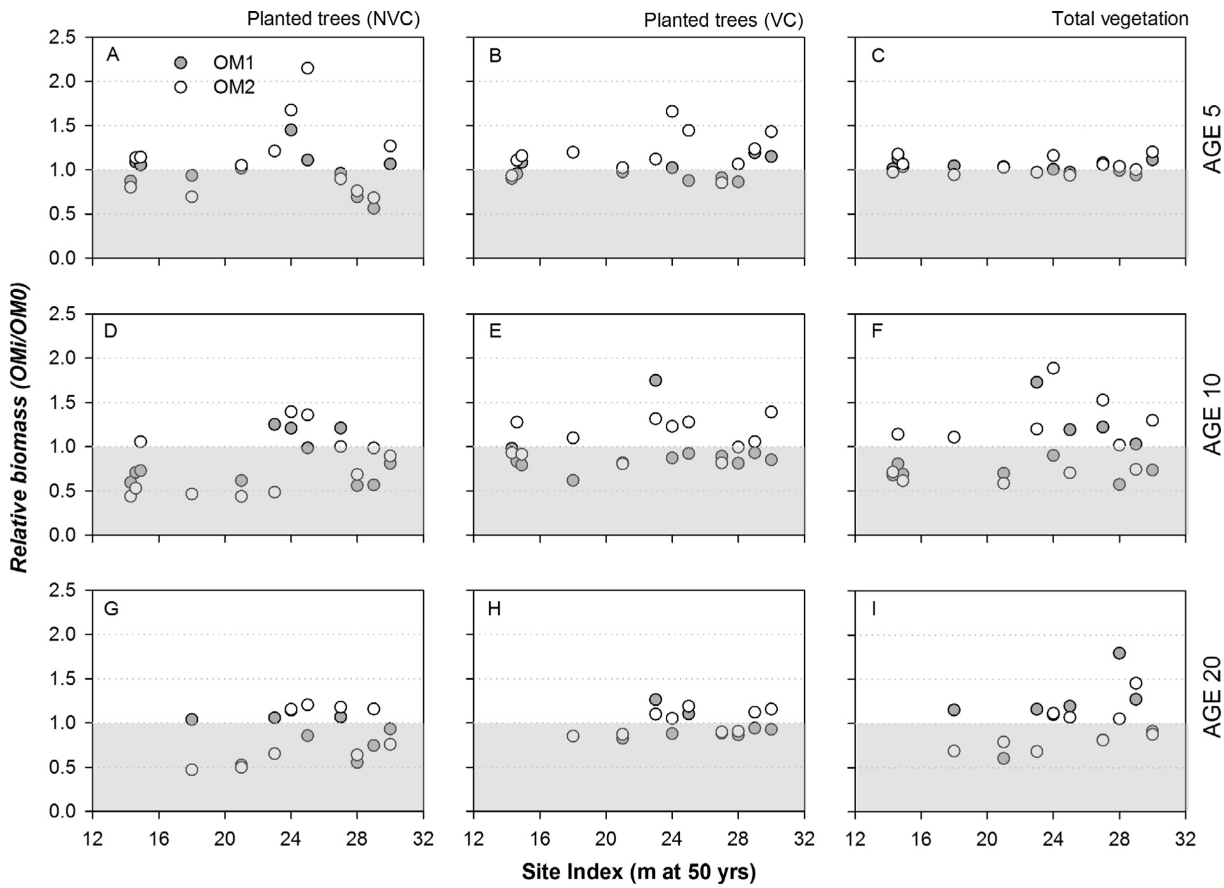

Fig. 5. Relative biomass of both whole tree removal (OM1) and whole tree plus forest floor (OM2) to bole only harvest (OM0) for planted trees with and without competing vegetation control (VC, NVC respectively), and for total vegetation (trees + competing vegetation) on the California LTSP installations varying with site index at age 5, 10, and 20. The 3 lowest-index sites have not been measured at age 20.

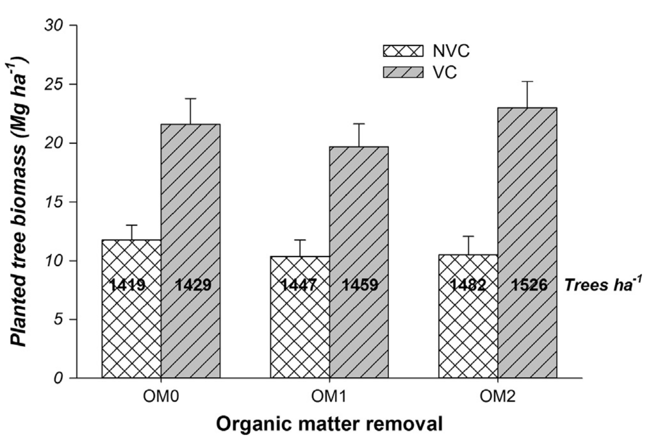

Fig. 6. Aboveground biomass (NPP: mean + 1se) for planted trees grown ten years under three levels of organic matter removal, split by VC and NVC treatments on the California LTSP installations. The numbers in the bars are planted tree density at age 10.

the significant compaction effect on tree biomass disappeared ($P > 0.631$; data not shown) at ages 5, 10, and 20. Therefore, it was not the compaction that increased biomass. Instead, more tree biomass resulted simply from a higher survival of planted trees in compacted plots versus non-compacted plots, which is consistent with results found in a young ponderosa pine stand without mortality (Zhang et al., 2013b). Fewer surviving trees would presumably grow larger in the same time period, having more available resources per tree, but this apparently was not able to compensate for a stocking density effect for the 20-year-old stands, which just reached about 1/4 to 1/3 expected rotation length (60–80 years).

The lack of significant negative effects of compaction in our installations raises an obvious question: Was the compaction technique utilized effective in physically increasing soil density? Compared with conventional logging operations, the methods and procedures that were used to compact soils at LTSP installations greatly exceed levels of operational logging compaction, in severity and in aerial extent. Data from soil bulk density core sampling and soil strength with cone penetrometer sampling confirm that soil bulk density and soil strength were substantially increased (by 10–25% soil bulk density) for both C1 and C2 treatments (Gomez et al., 2002; Page-Dumroese et al., 2006; Powers et al., 2005). In California installations, the objective was to reach 80% of the theoretical growth limiting soil bulk density (GLBD) (Daddow and Warrington, 1983). GLBD varies numerically with soil texture, ranging from 1.44 to 1.73 g cm^{-1} for the CA sites. Soils were compacted to 81–85% of GLBD at two of the 12 sites (unpublished data). Another 4 sites reached 70% and the remaining 6 sites were only 54–68% GLBD, suggesting that despite the level of effort in applying the compaction treatments, soils at most sites were not compacted to a level that prevented root growth. However, the United States Forest Service standards at the time defined "detrimental" soil compaction as >10% reduction in total soil porosity, as calculated from bulk density, which then could not exceed 15% of the area being impacted (severity + extent metrics). All of the sites reached this level of compaction, with six of the sites reaching 15–24% reduction in porosity with C2; six of the sites also exceed 10% porosity reduction with C1, in nearly 100% of the area.

Table 3
Probability (Pr > F) for testing treatment effect for periodic annual increment for tree biomass (paiAGB), projected canopy cover (PCC) and total crown volume (CrVol) for planted trees on California LTSP installations at ages 10 and 20. Num df and Den df are the numerator and denominator degree of freedom. Age 20 has 3 fewer sites included.

Source of Variation	Num df	Age 10					Age 20			
		Den df	pai AGB	Den df	PCC	CrVol	Den df	pai AGB	PCC	CrVol
Organic Matter (OM)	2	75	**0.018**	84	0.056	**0.035**	60	0.230	0.185	0.342
Compaction (C)	2	75	**<0.001**	84	**<0.001**	**0.006**	60	0.052	0.167	0.097
OM x C	4	75	0.162	84	0.095	0.266	60	0.068	0.155	0.096
Vegetation Control (Veg)	1	84	**<0.001**	92	**<0.001**	**<0.001**	65	**<0.001**	**<0.001**	**<0.001**
Veg x OM	2	84	0.260	92	**0.036**	0.078	65	0.595	0.511	0.364
Veg x C	2	84	0.694	92	0.604	0.511	65	0.625	0.766	0.485
Veg x OM x C	4	84	0.669	92	0.755	0.778	65	0.520	0.268	0.200

Bold values refer to significant effects at p < 0.05.

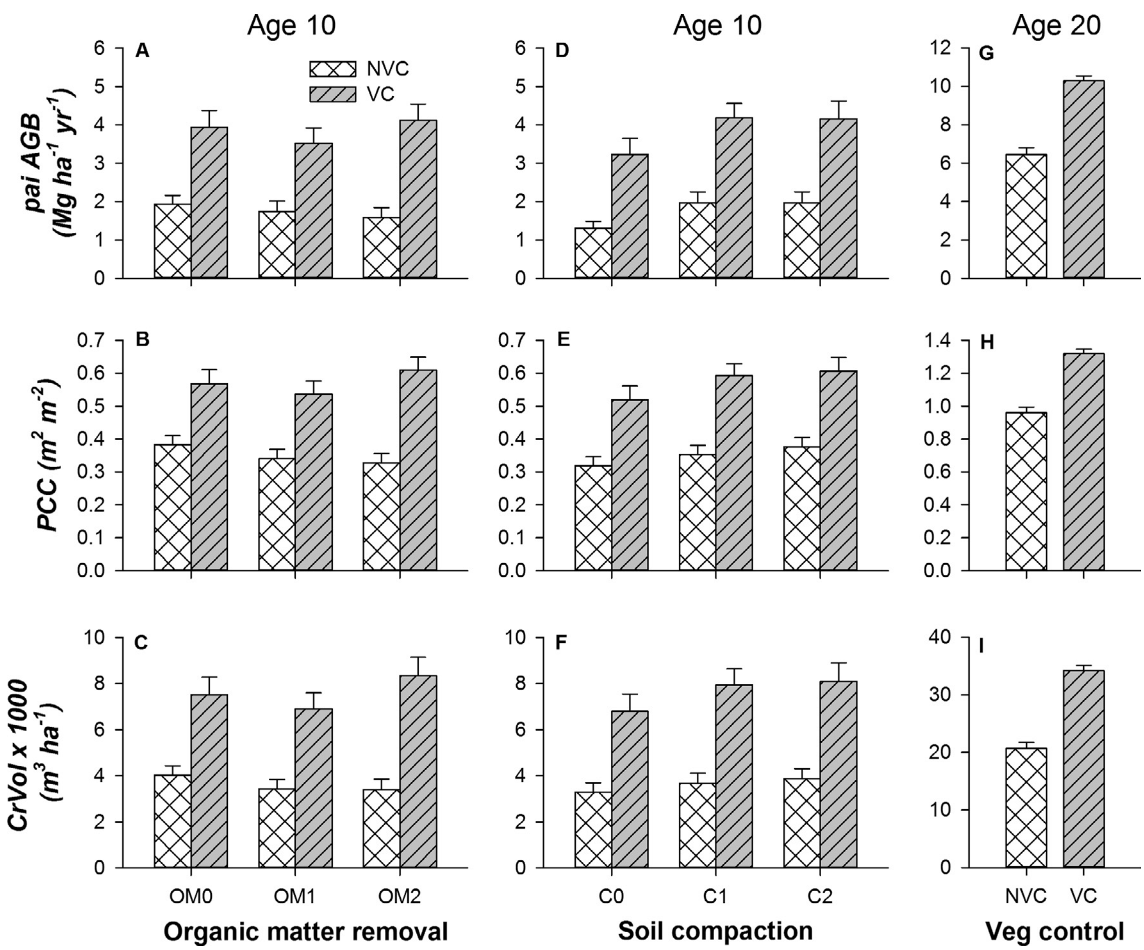

Fig. 7. Periodic annual increment for aboveground biomass (paiAGB), projected canopy cover (PCC), and crown volume (CrVol) for planted trees, separately by three levels of either organic matter removals (A, B, C) or soil compaction (D, E, F), split by VC and NVC treatments at age 10 and by only VC and NVC at age 20 on California LTSP installations. The paiAGB was calculated over the last five year period at age 10 and over the last ten year period at age 20.

Thus, the compaction treatment was effective in physically increasing soil density, and, by standard measures at the time, was sufficiently severe and extensive to expect a strong response by trees and competing vegetation.

The lack of response by trees to soil compaction may be due to their roots accessing old root channels left from the previous vegetation, which were not decomposed and could not be compacted when treatments were applied. Nambiar and Sands (1992) found similar growth rates of newly planted *Pinus radiata* comparing those planted in non-compacted soils versus planted in severely compacted soils that had also received perforations to simulate old root channels. But, they observed water and nutrient deficiencies in trees grown in compacted soils lacking simulated root channels. The same phenomena may have occurred in our study. However, in a root study conducted in three LTSP sites in California, Busse et al. (2017) found that despite consistently high soil strength values (>3 MPa), there were extensive numbers of roots in the compacted plots and no difference was found among compaction treatments. They speculated that while the soils were indeed compacted, total meso-porosity was still relatively high (>50%) leaving ample room for roots to grow.

Another possible explanation is that the compaction improved water holding capacity on sandy or sandy loam soils (Aries et al., 2005; Gomez et al., 2002; Siegel-Issem et al., 2005). Eight of the 12 LTSP sites had sandy loam texture (Table 1) and all had a Mediterranean climate with droughty growing seasons. Any

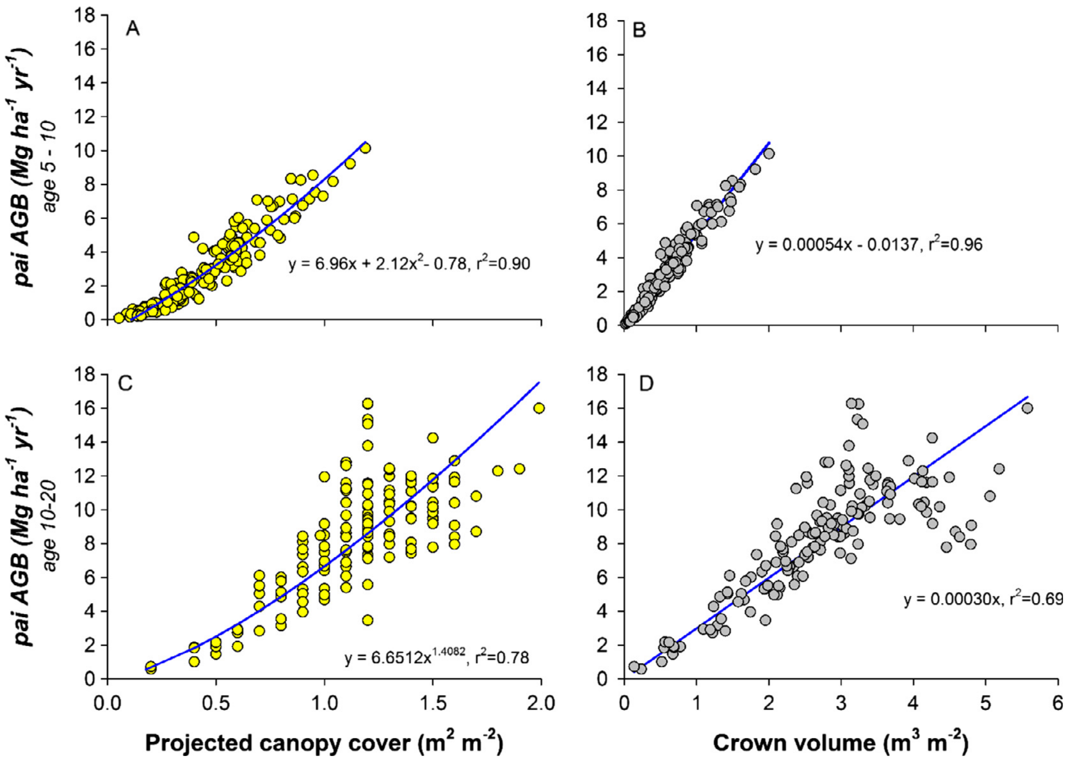

Fig. 8. Relationships between periodic annual increment for aboveground tree biomass and either projected canopy cover or crown volume for planted trees grown on California LTSP installations; data are from 12 sites at age 10 and 9 sites at age 20. Regression equations and r^2 are for those regression lines.

Table 4
Mean aboveground biomass and density of planted trees separated by species grown under organic matter removal by compaction treatment combinations, split by competing vegetation control, in nine California LTSP installations at age 20.

Veg treatment	Organic matter	Compaction	Planted tree biomass ($Mg\ ha^{-1}$)					Planted tree density ($trees\ ha^{-1}$)				
			ABCO	PILA[a]	PIPO	PSME[a]	SEGI[a]	ABCO	PILA	PIPO	PSME	SEGI
NVC	OM0	C0	1.1	2.4	69.2	3.1	12.9	61	124	922	130	142
		C1	1.3	2.6	52.9	8.9	17.8	140	151	892	284	223
		C2	1.8	2.8	71.0	7.5	21.9	146	122	890	242	239
	OM1	C0	1.0	0.8	42.0	2.8	13.3	121	74	756	140	166
		C1	1.5	2.1	58.9	6.3	23.9	134	122	821	226	303
		C2	1.3	2.3	65.7	5.2	20.7	150	122	846	219	260
	OM2	C0	0.6	2.2	54.7	5.1	18.6	102	124	890	213	261
		C1	1.0	3.6	53.4	5.3	22.9	145	142	730	224	264
		C2	3.6	2.4	46.9	6.6	18.2	140	132	777	225	255
VC	OM0	C0	1.2	5.0	93.3	6.7	19.0	53	147	900	150	152
		C1	3.2	5.9	98.2	11.7	35.8	143	158	902	230	268
		C2	2.9	3.7	109.1	9.9	32.0	138	122	953	218	277
	OM1	C0	2.2	3.9	83.8	9.2	20.7	111	131	846	200	176
		C1	2.5	4.7	91.4	15.7	42.7	163	143	826	307	340
		C2	3.3	4.9	89.4	10.8	36.9	138	152	861	263	291
	OM2	C0	2.0	5.3	93.6	7.3	38.8	176	160	801	239	324
		C1	2.4	6.5	91.0	8.4	40.2	192	177	806	271	320
		C2	3.4	6.5	90.3	7.2	31.7	218	166	783	214	315

Species Code: white fir (ABCO), ponderosa pine (PIPO), sugar pine (PILA), Douglas-fir (PSME), and giant sequoia (SEGI).
[a] Because these three species were not planted at every site, their tree biomass and density were the means among their planted sites.

treatment that would improve water availability would increase seedling survival (Powers and Ferrell, 1996) and improve biomass accumulation. Soil compaction increased soil moisture availability about 75% to a depth of 45 cm and improved mid-day xylem water potential by 22% during the summer at the sandy loam site at Rogers (Gomez et al., 2002). Yet, analyses of current data for those sandy loam sites indicated that tree biomass was only related to tree density. Planted tree 20-year biomass was not exclusively higher in the compacted plots than in the non-compacted plots at the Rogers site.

Increased soil water availability and improved growing season soil temperatures through enhanced thermal diffusivities and unsaturated hydraulic conductivities when vegetation was young (cf. Fleming et al., 2006; Page-Dumroese et al., 2006) promote seedling survival and growth (Kozlowski et al., 1991). In these installations, although two seedlings were carefully planted at each spot, survival rates were higher in the compacted plots than in the non-compacted plots at most sites (Fig.2C, F, I). In addition, soil disturbance caused by moving and replacing forest floor materials and compacting soils may have increased the direct contact between seedling roots and mineral soil, therefore modifying seedling nutrient uptake and survival (Gomez et al., 2002).

In summary, despite measurable alteration of soil properties, such as soil bulk density, total soil porosity, soil temperature, and soil water holding capacity, compaction did not affect total vegetation biomass. However, it increased tree biomass through enhanced tree survival, demonstrating the adaptive resilience of mixed conifer species to soil compaction.

4.2. Organic matter removal

We failed to detect any significant negative effects on trees biomass by OM1 and OM2 treatments at age 5, 10, and 20, or on total biomass at age 10 and 20 (Table 3). Although a significant difference in total biomass was found among OM treatments at age 5, total biomass was unexpectedly the highest in OM2. Therefore, we reject the second hypotheses that whole tree harvest or the same with additional forest floor removal would reduce aboveground biomass, and that the effect would be stronger as the stands developed. A caveat that must be provided here is that the non-significant negative trends for OM1 and OM2 compared to OM0 at age 10 and 20 warrant continued study, especially on lower quality sites (Fig. 5).

Concerns about the effects of whole tree harvesting compared to stem only removal on sustainable forest productivity have been extensively reviewed (Achat et al., 2015; Egnell, 2017; Thiffault et al., 2011; Wall, 2012). The unanimous conclusions were that whole tree harvesting or harvesting whole tree plus forest floor or stumps significantly depletes total and available soil nutrients, and negatively impacts other properties and processes such as soil organic matter, microbial activity, and decomposition (Powers et al., 2005; Smolander et al., 2013). Despite such changes in soil properties, the effects of whole tree harvesting on subsequent stand growth is less conclusive; a majority of studies have shown no effect on tree biomass (Holub et al., 2013; Ponder et al., 2012; Thiffault et al., 2011; Wall, 2012). Thiffault et al. (2011) concluded that soil productivity responses to whole tree harvesting were related to climate and microclimate, mineral soil texture and organic C content, base cation mineralogy, P availability, and autoecology of regenerating species. Our results from California LTSP installations in mixed conifer forests are in agreement with these studies (Fig. 3).

This presents an interesting question: did the OM1 and OM2 treatments significantly alter the soil properties at these installations? An early study found considerable declines in soil C and N concentrations and in potentially mineralizable N from whole tree plus forest floor removal (OM2) on four central and southern Sierra Nevada installations (Powers et al., 2005). The declines were likely due to reduced microbial decomposition caused by drier soil resulting from no forest floor cover (Powers and Fiddler, 1997). The latest data from these sites also showed that N was 15–20% lower in OM2 than in OM0 or in OM1 at year 10 and year 20 (unpublished data). Therefore, OM treatments did affect soil nutrient dynamics.

There are two possibilities as to why changes in soil nutrient status did not decrease aboveground biomass: (1) most of these installations were established on deep, relatively productive soils where nutrient limitations are less likely to occur due to greater quantities and proportions of nutrients left on-site (cf. Ponder et al., 2012). Johnson and Curtis (2001) found that a 6% reduction of C and N by whole tree harvesting was apparently non-significant for subsequent stand growth. (2) Soil microorganisms might enhance tree nutrition by utilizing otherwise inaccessible organic and/or mineral nutrient reserves (Kranabetter et al., 2006; Paul et al., 2007).

Although these explanations may be unprovable at this time, we observed no negative impact of complete organic matter removal on stand level biomass, at least to stand age 20. Murphy et al. (2004) also found no effect of forest floor removal on *Pinus radiata* plantation stem volumes at age 20 in a study on the North Island, New Zealand. A review of Nordic trials indicated that compared to stem only harvest, the effect of whole tree harvest on subsequent stand volume was site and/or species specific; the effect was negative for *Picea abies* yet there was no effect for *Pinus sylvestris* (Egnell, 2017). Therefore, it appears that conifers, especially pine species, are resilient to surface organic matter disturbance. Since the stand development of most of our plantations is close to the self-thinning stage (Fig. 8D), we speculate that organic matter treatment effects on tree biomass may not change throughout this rotation, at least on higher quality sites.

4.3. Competing vegetation control

Controlling competing vegetation enhanced both biomass, paiAGB, and canopy volume and PCC of planted trees (Fig. 2A, D, G; Fig.7A-C, G-I). But, it reduced total biomass in early stand development at ages 5 and 10 (Fig. 2B, E) due to the lack of competing vegetation that can accrue leaf area and biomass. More importantly, its effect on total biomass disappeared at age 20, suggesting rapid tree growth in stand development progression, and possibly attainment of site occupation capacity for total vegetation from age 10 to age 20 (Zhang et al., 2013a, 2016a). There was a general lack of interactions between vegetation control and either soil compaction or organic matter removal, or their three-way interactions. Therefore, we fail to reject the third hypothesis that vegetation control will increase the tree biomass throughout stand ages prior to an onset of self-thinning or artificial thinning, and that the VC treatment shall not influence the effect of soil compaction. However, our prediction that VC would modify the effect of OM removal by reducing the nutrient uptake demand by competing vegetation was not confirmed. The depletion of nutrients resulting from our excessive removal of surface organic materials might be relatively small compared to the entire nutrient pools in the soil.

Many studies demonstrate that vegetation control enhances early stand productivity, with percentage volume gains ranging up to four orders of magnitude (Wagner et al., 2006). This enhancement usually reflects a combination of growth reduction and lower survival on NVC plots compared to VC plots. Gains often vary with treatment duration, understory vegetation composition, site quality, silvicultural treatments, and other environmental factors (cf. Zhang et al., 2013a). Nonetheless, the universal and significant positive effect found in this study confirms that this common practice aids in rapid establishment of plantations, especially at sites with aggressive competing shrubs.

4.4. Plantation growth efficiency and canopy effects

Due to the climate- and site-induced variation of growth, and therefore differences in stand developmental stage among different installations, it may be more appropriate to evaluate stands in the same developmental stage rather than at equivalent ages (Waring, 1983). Here, we use projected canopy cover as a surrogate measure of leaf area index, and crown volume as a measure of the amount of solar radiation trees can absorb. Results showed that young stands had steeper slopes at age 10 than at age 20 (Fig. 8); more precisely, paiAGB appeared to change regression slopes after PCC reached 1.2 $m^2\ m^{-2}$ or crown volume reached 30,000 $m^3\ ha^{-1}$, suggesting their growth efficiency (biomass accumulation per leaf area or volume) decreased with stand development. Similar trends have been reported in various forest species (Oren et al., 1987). If the objective of managing stands is for timber production or maximum carbon uptake, repeated thinnings at this point of the developmental stage can maintain the lower crown for active photosynthesis (Helms, 1972). In addition, frequent thinning can also promote stand health for increased resilience to biotic disturbance such as bark beetles (Zhang et al., 2013) and hasten the move to larger diameter trees that are more resistant to wildfires.

5. Conclusions

Twenty-year vegetation data presented here not only confirm the general trends found at ages 5 and 10, but also strengthen our confidence to conclude: (1) compacting soils at these California sites will not pose a negative effect on aboveground biomass for either planted trees or total vegetation, despite reductions in total soil porosity, increases in soil temperature early on, and increases in soil water holding capacity. Positive effects of compaction on tree biomass were through enhanced tree survival, which should not be interpreted as compaction increased site productivity. (2) Compared to stem only harvesting, both whole tree harvesting and whole tree plus forest floor removal did not significantly affect aboveground biomass. If there was an OM effect, it occurred from age 5 to age 10, which might be due to the alteration of microclimate by removal of surface organic materials, particularly the forest floor. However, modest temporal changes in biomass response to OM removal calls for continued study, especially at lower quality sites. (3) Vegetation control increased tree biomass for 20 years, and decreased the total vegetation biomass in early stand development years. By age 20, similar sites were occupied with the same amount of total biomass whether treated or not. (4) A lack of general interactions among vegetation control, compaction, and organic matter removal provides an opportunity to examine site-related effects in future analyses. Our caveat for these conclusions is that this study focuses on treatment effects on vegetation productivity and development. Effects on soil processes such as soil hydrologic function and other ecosystem services were not tested here, and could be significant.

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