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Effect of redistributing windrowed topsoil on growth and development of ponderosa pine plantations

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This paper is dedicated to the memory of an esteemed colleague, Dr. Robert F. Powers, who designed and oversaw the installation and early data collection of this experiment.

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Windrowing site preparation
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ABSTRACT

Windrowing site preparation often displaces significant amounts of topsoil including nutrients and carbon into the strip-piles. Although short-term growth may increase due to the early control of competing vegetation, this practice can reduce long-term plantation productivity. Here, we report an experiment established in 1989 in a 28-year-old ponderosa pine (*Pinus ponderosa*) plantation to determine if redistributing topsoil, along with several shrub control measures, have influenced soil fertility and tree growth. Five treatments from a partial factorial design with three levels of shrub treatment and two levels of soil manipulation were applied in each of five blocks and consisted of: Control (C, do nothing); understory hydroaxed (masticated) to chips and left in the plot (H); windrows redistributed over brush (S); understory hydroaxed and windrows redistributed over chips (SH); and understory manually removed off-site and windrows redistributed (SM). Over the next 21 year period total windrowed topsoil volume and mass were determined, soil nutrient concentrations in and between windrows including soil mineralizable N, total N and C were determined, understory biomass measured, tree diameter, basal area, and volume measured in 1989, 1994, 2005 and 2010, and nitrogen concentration of tree foliage was measured in 1989, 1991 and 1994. Results showed that about 18 cm of topsoil had been displaced into windrows, including 1.98 (±0.13) Mg N ha^{-1} and 41.04 (±2.46) Mg carbon ha^{-1}. In general, redistributing windrowed topsoil (S, SH, and SM) yielded a consistently positive effect on quadratic mean diameter, basal area (BA), and volume compared to C and H. No difference in growth was found between SH and SM. These results were supported by higher soil nitrogen and mineralizable nitrogen contents in the three topsoil redistribution treatments. Higher foliage nitrogen concentrations in the redistribution treatments further supported these higher tree growth rates. The positive effects of shrub removal were evidenced only on the treatments without topsoil redistribution (C versus H); the difference in BA and volume between C and H was only significant in 1994. Redistributing topsoil reduced woody plant biomass but significantly enhanced herbaceous biomass six years after treatment. This shows that windrowing site preparation reduces plantation growth and stand development through displacement of topsoil and its nutrients. These negative effects can be mitigated by carefully redistributing windrowed topsoil, even in an established plantation.

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1. Introduction

Windrowing is a site preparation operation, usually performed by machine, which piles debris and shrub slash in linear rows immediately prior to planting (Helms, 1998). The primary objectives are to increase survival and growth of planted trees by improving the seedling microsite and controlling competing vegetation. Increased access, lower fire risk, and reduced pests are secondary objectives (Atzet et al., 1989). This practice, however, directly impacts surface soil, or topsoil, where organic matter and labile nutrients are disproportionally concentrated in the soil profile (Powers, 1990; Powers et al., 1990). Tew et al. (1986) estimated that displacement of surface materials into windrows removed two to three times more N and P than does whole-tree harvesting. Because temperate and boreal forests can store as much as three times more nutrients in the forest floor than in the standing forest (McColl and Powers, 1984), windrowing has a significant impact on nutrient displacement and subsequently site

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productivity (Morris et al., 1983; Dyck and Beets, 1987; Powers et al., 1988; Fox et al., 1989).

During the 1950s and 1960s, many plantations were established using windrowing methods in the United States and across the world (Fig. 1). The direct impact of such practices on early plantation productivity often was confounded by reduced weed competition (Powers et al., 1990). For example, volume growth for a *Pinus taeda* plantation grown on windrowed sites as compared to those with intact topsoil significantly increased at age 3 in Alabama, which was mainly due to plant competition reduction (Tuttle et al., 1985). However, volume was similar at age 12 in Louisiana (Haywood and Burton, 1989). Because topsoil displacement also reduced weed competition, fertility losses were confounded with reduced competition.

In New Zealand's pumice region, displacing logging debris and a thin layer of topsoil into windrows during site preparation produced nutrient deficiency and led to a 30% loss in volume growth in a 17-year-old *Pinus radiata* plantation (Dyck and Beets, 1987). In the North Carolina Piedmont, windrowing on a Typic Hapludult soil led to a 23% volume growth reduction at 25 years (Fox et al., 1989). Powers et al. (1988) compared nutritional characteristics of 22 established plantations of ponderosa pine (*Pinus ponderosa*) in California and Oregon that had or had not been windrowed during site preparation. Although results were confounded somewhat by differing soil types, windrowed plantations averaged one-third less mineralizable soil N, one-tenth less foliar N, and one-third lower site indices than non-windrowed plantations. Nitrogen fertilization produced four times the relative volume growth response in windrowed plantations versus non-windrowed ones.

Mitigating the impacts of windrowing on these maturing plantations can be difficult. As far as we are aware, no studies have been reported showing before and after results from redistributing topsoil. Moreover, few studies have aimed to test if windrowing affects long-term stand productivity and overall ecosystem health. Here, we report results from a well-designed experiment initiated by the late Dr. Robert Powers in 1989 to determine if and how topsoil redistribution and shrub control affects soil productivity and tree growth in an established plantation.

2. Materials and methods

2.1. Study site

The study is located in Northeastern California on the Doublehead Ranger District, Modoc National Forest (Lat. 41.33N; Long. 121.27W). Elevation is about 1650 m. Site index is 22 m at 50 years. Slopes average about 15% gradient with an easterly aspect. Soils are of volcanic origin where pumice, ash and cinders were deposited on the lower side slopes of Medicine Lake volcano. The USDA soil series is Tionesta, classified as a pumiceous or ashy-pumiceous over medial-skeletal, mixed, frigid, Typic Haploxerand; the textural class and modifier of the topsoil is very gravelly loamy coarse sand. From the spline climate surfaces at the site for 1950–2004 (Rehfeldt, 2006), average annual precipitation is about 520 mm at the site. Mean annual temperature is 6.7 °C. Maximum temperature in the warmest month is 27.8 °C and minimum temperature in the coolest month is −8.9 °C. Growing degree-days (>5 °C) is about 1560.

The site was windrowed by bulldozer in 1960 and planted with ponderosa pine seeds in the fall of 1961. The plantation grew up with a dense understory mainly of greenleaf manzanita (*Arctostaphylos patula*), snowbrush (*Ceanothus velutinus*), bush chinquapin (*Chrysolepis sempervirens*) and a few other minor species. The plantation was thinned from below in 1987 by removing trees from lower crown classes to favor those in the upper crown classes. The residual trees averaged dbh 18.3 cm and height of 7.3 m.

2.2. Treatment design and application

The experiment was established in the fall of 1989 and consisted of five treatments which were randomly assigned to each of five blocks (Fig. 1). They are: control (C, do nothing); understory hydroaxed to chips which were left in the plot (H); windrows redistributed by bulldozer over brush (S); understory hydroaxed and windrows redistributed over chips (SH); understory removed manually and windrows redistributed (SM). Hydroaxe (Blount, Inc., Zebulon, NC, USA) is one type of mechanical rotary shredder to masticate brush into chips, commonly used at the time. Treatment plot size is 0.12 ha and the measurement plot is the inner 0.06 ha. The blocks were arranged generally along the contour between the windrows. Treatment characteristics for trees are shown in Table 1.

2.3. Tree measurements

In 1989 all trees in the measurement plots were individually tagged and measured for height and diameter at 1.37 m (dbh) immediately after the treatments were applied. Marked staffs were used for precise dbh height. Trees within one meter distance from and on the windrow, or where the windrow had been prior to treatment, were separated for future comparison. Tree height and dbh were re-measured in 1994, 2005, and 2010. In the first three measurement periods, three trees representing small, average, and large size from each plot were selected, and total stem volume inside bark was determined using a Barr-Stroud FP15 optical dendrometer and application of a regional bark thickness equation

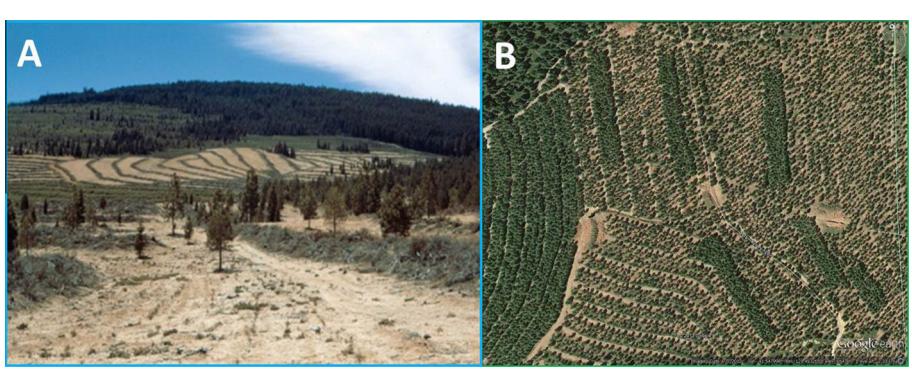

Fig. 1. Windrowing site preparation (A) and 54-year-old plantation (B) in which a 2012 thinning for fuels reduction was conducted around the research blocks (5 rectangular strips). Picture B is adapted from Google Earth.

Table 1
Means and standard errors of height, quadratic mean diameter, basal area, volume, and trees per hectare for ponderosa pine trees when five treatments were applied in 1989, and 21 years later in 2010.

Year	Treatment	Trees (ha^{-1})	Height (m)	QMD (cm)	BA (m^2 ha^{-1})	Vol (m^3 ha^{-1})
1989	C	264 (21)	7.47 (0.49)	18.4 (1.0)	7.85 (0.77)	34.08 (4.15)
	H	303 (9)	7.30 (0.30)	18.1 (0.5)	7.31 (0.50)	30.20 (2.72)
	S	290 (14)	7.40 (0.39)	18.5 (1.0)	7.86 (1.11)	33.87 (5.37)
	SH	303 (14)	6.19 (0.61)	15.5 (1.4)	5.52 (1.23)	21.77 (5.35)
	SM	247 (12)	7.43 (0.63)	18.0 (1.6)	7.09 (1.34)	30.26 (6.69)
2010	C	261 (20)	18.49 (0.62)	37.9 (1.0)	32.81 (1.37)	220.31 (10.99)
	H	300 (10)	18.91 (0.56)	39.3 (1.0)	33.81 (1.66)	220.53 (13.75)
	S	290 (14)	19.14 (0.54)	41.7 (0.4)	38.67 (2.74)	267.29 (24.57)
	SH	303 (14)	18.17 (0.68)	39.0 (0.9)	33.23 (2.93)	207.05 (22.23)
	SM	244 (11)	19.56 (0.79)	40.8 (0.9)	34.53 (2.48)	242.69 (25.58)

Note: C = control; H = understory hydroaxed to chips; S = windrows redistributed; SH = hydroaxed and windrows redistributed over chips; SM = understory removed manually and windrows redistributed.

(Cochran, 1976). Section volumes from standing trees were computed as frusta of a cone. A treatment specific tree-level volume equation based on $V = a + b * \text{dbh}^2 * \text{height}$ was then developed for determining individual-tree volume in 1989, 1994, and 2005. The volume determination for the last measurement in 2010 followed the allometric equations developed in 2005.

From these individual tree data, we calculated average tree height, quadratic mean diameter (QMD), basal area (BA), and volume for each plot.

2.4. Understory biomass

Aboveground understory biomass (Mg ha^{-1}) was sampled in twenty 3.142 m^2 subplots within five treatments across five blocks prior to the treatments in 1989, and in five 0.785 m^2 subplots per treatment plot in 1995. Dominant shrubs, including greenleaf manzanita and snowbrush, were measured separately from other shrubs, which also included a few grasses and forbs of minor amount. In 1995 grasses and forbs were additionally separated from "other shrubs" as these vegetative components had greatly increased. Fresh weight of the understory biomass was measured in the field on a lab scale (OHAUS I-20W) in tared batches to the nearest gram, and subsampled to determine the water content and extrapolate the dry-weight biomass. Subsamples were dried at 70 °C and repeatedly weighed on a precision lab scale (0.01 g) until they reached constant mass. Dominant grass species surveyed on August 13, 1996 included California needlegrass (*Achnatherum occidentale* ssp. *californicum*) and squirreltail (*Elymus elymoides*) across all plots where topsoil had been redistributed. California brome (*Bromus carinatus*) was also a dominant species in a few plots. *Carex* spp. grew in all plots.

2.5. Forest floor and coarse woody debris

Forest floor biomass and coarse woody debris were measured in all subplots (sampling for understory biomass) in 1995. However, only forest floor biomass was measured in 1989. Forest floor material was collected from five 0.25 m^2 quadrats per plot, which were delineated with a metal frame extending to the mineral soil surface. All wood ⩾ 1 cm diameter within the metal frame were also collected as "coarse woody debris." The whole sample was oven dried and weighed as per understory vegetation.

2.6. Nutrients in plant materials

Pine needle foliage was collected from five trees from the top third of the south face of the crown and composited from each plot in 1989, 1991, and 1994. The current year and previous year needles were separately sampled. Foliage was dried and ground in a Wiley mill. Foliar N was then analyzed using the combustion method (Leco Corporation, 2003). In addition, nitrogen concentrations of crown and stem were analyzed separately for understory shrubs including greenleaf manzanita, snowbrush, and other species in 1989 and 1995. Nitrogen concentration for the forest floor was analyzed to estimate this N pool for both 1989 and 1995. For coarse woody debris analysis, nitrogen concentrations of tree twigs and stems were used to estimate the N pool, as this material was almost exclusively fallen tree branches.

2.7. Soil physical and chemical analysis

In 1990, ten soil transects were examined which included two from each of the five control plots, beginning and ending on each side and running directly across the windrows. Profile height was measured at 10 cm intervals across the windrow. With these data and lengths of windrow segments, total volume of soil in each windrow was calculated. Soil bulk density for fine soil (2 mm or less) was obtained by analyzing several core samples within the profile and taking their average. Concentrations of soil N and C were then analyzed using the combustion method. Total mass of windrowed soil and N and C content were then determined. Five sample sites were randomly chosen in each plot in 1990 and 2010 to determine soil bulk density and total N, C, and mineralizable N. Soil samples were collected from four depths (0–10, 10–20, 20–30, and 30–40 cm). Soil samples from the same depth were oven-dried and weighed for soil bulk density before they were composited. After air-drying, soils were sieved to 2 mm and analyzed for mineralizable N according to the procedure of Powers (1980). To determine total soil N and C these samples were also analyzed using the combustion method. Concentrations were then converted to weight (kg ha^{-1}) using average bulk density per depth per plot. Although zero-level of the mineral soil surface changed with soil respreading, it was variable in using heavy equipment, and there was no way to compensate for the change in soil sampling; thus direct comparison of the depth increments between respread treatments (S, SH, and SM) and C and H treatments does involve some disparity.

2.8. Statistical analyses

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 MIXED (SAS Institute Inc., 2013). To take advantage of the study design, we analyzed data by separating our treatments into a partial factorial of three levels of "SHRUB" treatment (hydroaxed mastication, manual removal, and no shrub removal) and two levels of "SOIL" manipulation (with and without topsoil redistribution). The base model is:

$$y_{ijk} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \gamma_k + \varepsilon_{ijk}$$

where y_{ijk} is the dependent variable measured for the ith SHRUB, the jth SOIL, and the kth Block, μ is the overall mean, α_i is the fixed effect of the ith SHRUB, β_j is the fixed effect of the jth SOIL, $(\alpha\beta)_{ij}$ is

the fixed effect of SHRUB $*$ SOIL interaction, γ_k is the random effect of the kth block $\gamma_k \sim N(0, \sigma_B^2)$, and ε_{ijk} is an experimental error $\varepsilon_{ijk} \sim iid\, N(0, \sigma_e^2)$.

Because of the existing differences in tree size among plots when treatments were applied (Table 1), we used data from 1989 as a covariate for the post-treatment height, QMD, BA, and volume analyses. If dependent variables were not measured in 1989 (N, C/N, and mineralizable N) or did not vary significantly among SOIL, SHRUB, and their interactions (biomass of understory shrubs and herbaceous species, coarse woody debris, and forest floor and foliar N concentration), the covariate was not included in the model. For soil nitrogen and carbon/nitrogen ratio, we included depth and associated interactions as fixed effects to the model. Different sample years were separately analyzed to simplify the models using fewer parameters with fewer assumptions. 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 SHRUB by SOIL combinations 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

Because SHRUB and SOIL effects were significant for height, QMD, BA, and volume measured in 1989, we analyzed treatment effect on stand growth using 1989 data as a covariate. Neither SHRUB or SOIL effects, nor their interactions, were found to be significant for height in 1994 ($P > 0.17$). However, the effect of soil manipulation was significant ($P < 0.02$) in 2005 and 2010. In 2010, over 20 years after the treatments, shrub removal effect was only significant at $P = 0.07$. Multiple comparisons showed that height in control, not in H, differed significantly from height in S, SH, and SM ($P < 0.05$) in 2005 and in SH and SM in 2010 (Fig. 2A), respectively.

The three measurement years all showed significant SOIL effect ($P < 0.01$) and SOIL by SHRUB interactions for QMD ($P < 0.04$). The SHRUB effect was only significant in 1994 ($P < 0.01$). The topsoil redistribution (S, SH, and SM) significantly increased QMD compared to H and C ($P < 0.01$). QMD in H was also more than QMD in the do-nothing control (Fig. 2B).

Both BA and volume showed a significant SOIL effect in all measurement periods ($P < 0.01$). But the significance of the SHRUB effect and SOIL by SHRUB interaction varied among the periods. Multiple comparisons showed (Fig. 2C and D) that in 1994, only the do-nothing control had a significantly smaller BA and volume than other treatments ($P < 0.01$). In 2005 and 2010, the S treatment had the largest BA and volume, which was not significantly more than the SH and SM ($P > 0.05$), but was more than the H and C ($P < 0.05$). No significant differences ($P > 0.05$) in BA and volume between H and C and among H, SH, and SM were detected.

Trees growing within or immediately adjacent to windrows had significantly more volume ($\mu = 0.15 \pm 0.02$ m^3 tree^{-1}) than was found for trees growing between windrows ($\mu = 0.11 \pm 0.01$ m^3 tree^{-1}) when the treatments were installed at age 28 ($P < 0.01$). No interaction among tree position, SHRUB, and SOIL was found to be significant ($P > 0.10$). Twenty-one years after treatments were applied, this trend still held (0.99 ± 0.07 versus 0.80 ± 0.03 m^3 tree^{-1}). Using 1989 mean volume as a covariate, we found that the overall effects of tree position on average tree volume were not significant ($P > 0.73$) in 1994, 2005, and 2010.

3.2. Understory, coarse woody debris, and forest floor biomass

Understory biomass and forest floor were not significantly different among treatments in 1989 ($P > 0.289$). Greenleaf manzanita and snowbrush dominated the understory biomass with 6.01 (SE = 1.53) Mg ha^{-1} for greenleaf manzanita and 6.54 (SE = 1.71) Mg ha^{-1} for snowbrush, respectively. There was 0.06 (SE = 0.05) Mg ha^{-1} for other plant species. Forest floor biomass was 22.43 (SE = 3.31) Mg ha^{-1}.

In 1995, six years after treatments were applied, biomass of woody plants, herbaceous plants, coarse woody debris, and forest floor were all highly significantly different among or between SOIL, SHRUB, and SOIL $*$ SHRUB ($P < 0.001$). These differences were mainly caused by the low herbaceous biomass and very high biomass for other components in the control plots compared to other plots (Fig. 3A). Topsoil windrow redistribution significantly reduced the woody understory biomass, but promoted herbaceous growth.

3.3. Plant nitrogen status

In 1989 when treatments were installed, no treatments or their interaction were significantly different in foliar N concentrations, except that foliar N in the current year foliage was higher than N in the previous-year foliage (Fig. 4). In 1990 and 1991, only the SOIL effect was significant ($P < 0.001$) with higher foliar N on trees in the topsoil redistribution treatments (S, SH, SM) than for trees in C or H. Similar results were found in 1993 and 1994 except for trees in C in which foliar N was only significantly different from trees in S, SH, and SM at $P < 0.08$.

Understory woody plant nitrogen concentration did not significantly differ among treatments in 1995 ($P > 0.58$), but differed between crowns and stems ($P < 0.05$), and among *Arctostaphylos* (crown/stem: 0.47/0.23%), *Ceanothus* (0.90/0.64%), and other species (0.59/0.40%). N concentration trend was crowns > stems, and *Ceanothus* > others > *Arctostaphylos*. However, the trends of total N content followed the biomass pools (Fig. 3B). Total N content in understory woody species was 326.5 (±61.5), 29.4 (±13.3), 9.7 (±5.8), 2.5 (±0.7), and 1.4 (±0.6) kg ha^{-1} in C, H, S, SH, and SM, respectively. In 1989, N content in understory vegetation was 73.1 (±13.7) kg ha^{-1}; there were 20.9, 51.9, and 0.3 kg ha^{-1} in *Arctostaphylos*, *Ceanothus*, and other species, respectively.

Nitrogen concentration for forest floor averaged 0.71% (SE = 0.15), which was not different among treatments ($P > 0.38$). However, we did find a significant difference in N pools ($P < 0.001$) among the treatments. N content was about 134.1 (±12.710), 35.3 (±9.8), 12.7 (±3.2), 22.0 (±12.8), and 14.8 (±5.0) kg ha^{-1} for C, H, S, SH, and SM, respectively (Fig. 4B). In comparison, N content prior to the treatments was about 159.2 (±23.5) kg ha^{-1} in the forest floor, which is not significantly different from post-treatment controls.

Nitrogen content of coarse woody debris also differed among treatments with 10.6 (±2.2), 2.6 (±0.9), 3.1 (±1.2), 5.6 (±3.6), and 0.9 (±0.3) kg ha^{-1} for C, H, S, SH, and SM, respectively. No woody debris was analyzed in 1989.

Overall, nitrogen content of combined understory vegetation, coarse woody debris and forest floor was about 471.3, 72.3, 37.2, 42.6, and 29.1 kg ha^{-1} for C, H, S, SH, and SM, respectively.

3.4. Soil nutrients and carbon

The average windrow was 9.30 (±0.39) m wide and 0.48 (±0.01) m deep. Bulk density for fine soil in windrows was 0.58 (±0.01) g cm^{-3}. Combustion N was 0.19% (±0.01) and C was 3.96% (±0.20). A total of 1808.75 (±81.05) m^3 ha^{-1} of fine soil containing 1.98 (±0.13) Mg N ha^{-1} and 41.04 (±2.46) Mg carbon ha^{-1} was

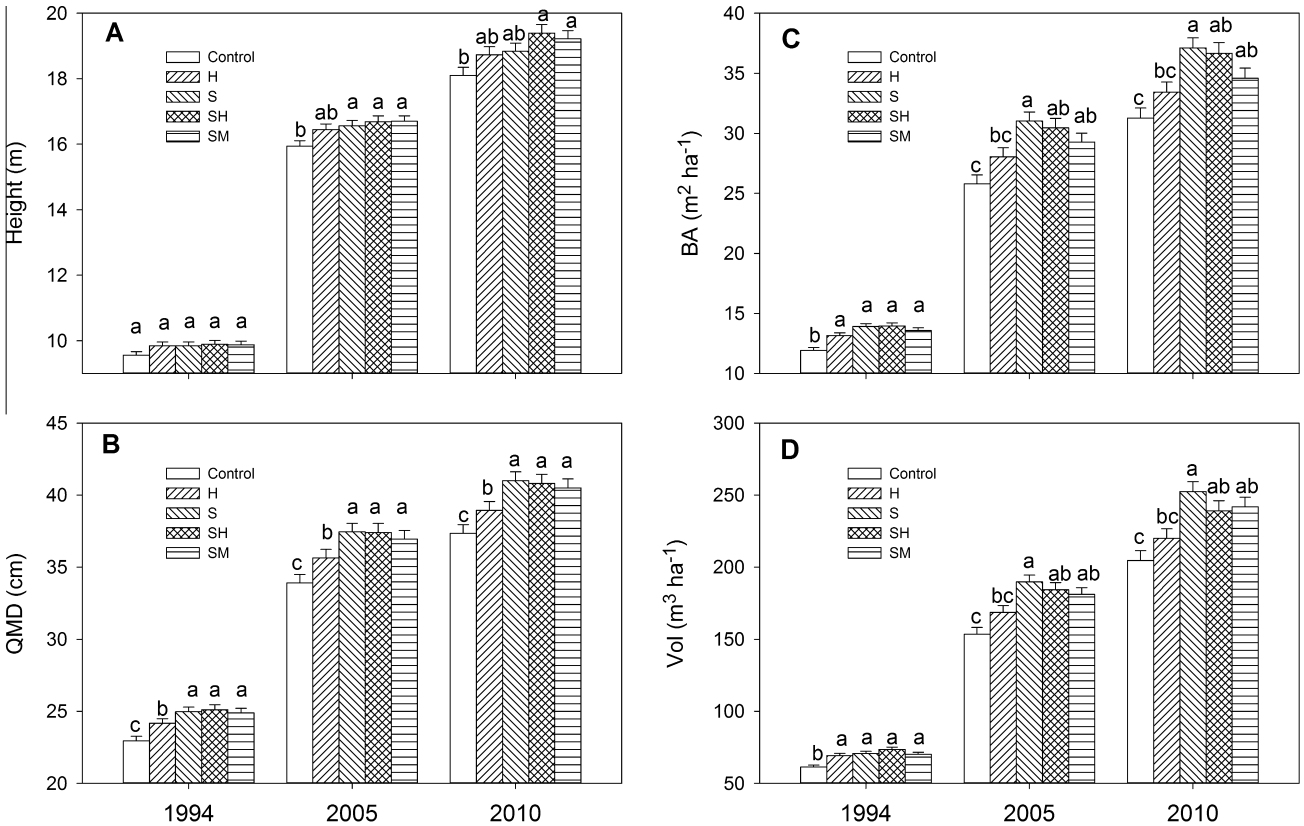

Fig. 2. Least squares means using the starting data (1989) as covariates for height (A), quadratic mean diameter (B), basal area (C), and volume (D) for ponderosa pine grown on four treatment plots and control plots in northern California during three periods. H = understory hydroaxed to chips; S = windrows redistributed; SH = hydroaxed and windrows redistributed over chips; SM = understory removed manually and windrows redistributed. Bars with different letter within the same measuring year indicate difference at $P < 0.05$.

incorporated into windrows. The volume of windrowed topsoil was equivalent to 18.1 (±0.01) cm in depth throughout the experimental area.

One year after windrowed topsoil was redistributed across the respective plots, mineralizable soil N was estimated to be significantly higher at two lower sampling depths in the S, SH and SM plots than in the control. The SOIL effect and SOIL by depth interaction were significant ($P < 0.02$) regardless of whether shrubs were removed or not. With the topsoil redistribution, the only significant difference was found between the bottom depth (30–40 cm) and three upper depths (0–30 cm) (Fig. 5). Without topsoil being redistributed (C versus H), estimates of mineralizable N differed in the two upper depths (0–20 cm) from the two lower depths (20–40 cm).

For soil nitrogen content, we found significant effects of SOIL ($P < 0.01$), depth ($P < 0.01$), and SOIL $*$ SHRUB ($P = 0.03$) in 1990, and SOIL ($P = 0.02$) and SOIL $*$ SHRUB ($P = 0.03$) in 2010. The topsoil redistribution plots (S, SH, and SM) had consistently higher nitrogen content than that of the control and H plots for all soil depths in 1990 (Table 2). Upper depths of soil consistently contained significantly more N than the lower depths of soil. The significant interaction of SOIL $*$ SHRUB was mainly caused by substantially higher N in the S treatment in 1990 and 2010.

The effects of SOIL, depth, and SOIL $*$ depth in C/N ratio were significant in 1990 ($P < 0.01$). However, only the SOIL $*$ SHRUB interaction was significant in 2010 ($P = 0.02$). In 1990, no treatment difference was detected in the top 10 cm (Table 2). Yet, S or SH appeared to have higher C/N ratio than C and H. In contrast, no treatment differences were found at any depth in 2010. In 1990, all soil depths differed from one another without topsoil redistribution. With topsoil redistribution, only the upper two depths showed no difference in C/N. By 2010, the C/N ratio tended to decline substantially from 1990. Differences in C/N also disappeared among depths ($P = 0.39$).

4. Discussion

Results from this study provide some quantitative measures of amounts of soil and soil nitrogen and carbon that were displaced when windrowing site preparation was used to establish tree plantations, a widely used practice in the West in the 1950s and 1960s. The windrows in this study were substantially larger due to wider inter-windrow widths (approx. 28–35 m) and a more dense brush community than what was reported in the South (Morris et al., 1983; Pye and Vitousek, 1985; Tew et al., 1986). For example, Glass (1976) reported that 2.5 cm of surface soil was displaced on a 25-year-old raked and piled *P. taeda* plantation in the North Carolina Piedmont. Tuttle et al. (1985) reported that 8 cm of topsoil had been displaced. In one of the first root-raking operations in *P. radiata* in New Zealand, Ballard (1978) also found about 2.5 cm of topsoil had been displaced and pushed into the windrows along with the logging residue. Although such measurements were rarely done in the western US, the depths 2.5–8.0 cm were much smaller than 18 cm found in this study. This difference was perhaps due to the legacy vegetation of this plantation. The windrows in this study area were constructed in a brushfield with large amounts of *Arctostaphylos, Ceanothus,* and *Chrysolepis* with an aboveground biomass of 85.2 (±7.6) Mg ha^{-1} (Goslee et al., 2012). One could imagine that large amounts of soil were displaced when these

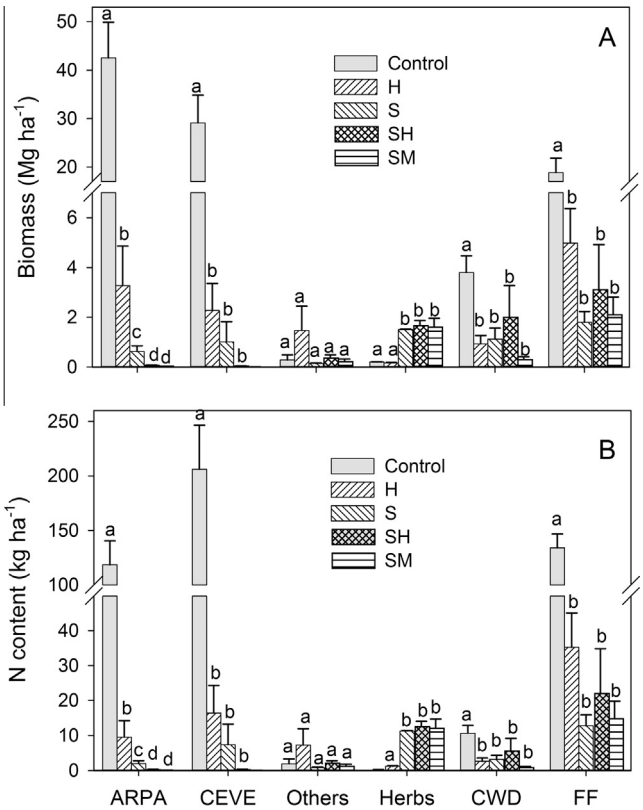

Fig. 3. Means and standard errors of (A) biomass (Mg ha^{-1}) and (B) nitrogen content (kg ha^{-1}) for *Archtostaphylos patula* (ARPA), *Ceanothus velutinus* (CEVE), and other understory woody plants (Others), herbaceous plants (HERB), coarse woody debris (CWD), and forest floor (FF) measured for all treatment plots in the summer of 1995. C = control; H = understory hydroaxed to chips; S = windrows redistributed; SH = hydroaxed and windrows redistributed over chips; SM = understory removed manually and windrows redistributed. Bars with different letter within the same species or category indicate difference at $P < 0.05$.

shrubs were piled into windrows. In addition, in cases (as here) involving aggressively sprouting shrubs, soil displacement was often purposeful to remove root crowns and delay or prevent re-sprouting of competing shrubs. In those studies in the southern US and New Zealand, the inadvertent displacement of topsoil was done while piling post-harvest logging debris with lesser amounts of brush.

We also found that significant amounts of nitrogen (1.98 ± 0.13 Mg ha^{-1}) and carbon (41.04 ± 2.46 Mg ha^{-1}) associated with the soil were windrowed. The amount of nitrogen in windrows was equivalent to about 80% of total nitrogen within the top 40 cm of soil measured in 1991 (Table 2). Due to the different soil types, we can only have a valid comparison between studies with known background nutrient levels. For example, Tew et al. (1986) reported that nitrogen content within the top 60 cm of soil was 4.51 Mg ha^{-1} and displacement of mineral soil into windrows was 0.16 Mg ha^{-1}, representing only 3.5%. In New Zealand, Dyck and Beets found that 23% of the soil N had been displaced during site preparation in a Pekepeke sandy soil after first rotation *P. radiata* was harvested (Dyck and Beets, 1987).

The effects of windrowing on plantation establishment and growth have been both positive and negative. The practice was originally justified by some demonstration plots in California showing that early survival and growth was greatest where mineral soils were most disturbed and most biomass was removed (Buck, 1959). The short term positive result was mainly due to better planting spots for either tree seeds or seedlings and effective competing vegetation control (Powers et al., 1990). The negative long term effect was the reduced availability of soil nutrients and organic matter by windrowing, which subsequently reduced plantation growth in *P. radiata* in Australia (Keeves, 1966) and in New Zealand (Ballard, 1978; Dyck and Beets, 1987), and *P. taeda* in the southern US (Fox et al., 1989; Tuttle et al., 1985). A direct measure of windrowing effects on growth in the western US has been limited. Powers et al. (1988) surveyed some ponderosa pine plantations in Northern California and southeast Oregon and concluded that windrowed plantations are nutrient deficient. On a 26-year-old ponderosa pine plantation growing on a droughty volcanic ash soil in California, Atzet et al. (1989) found that trees planted within 3 m of the windrows grew twice the volume of trees grown at a greater distance between the windrows. In this study, we found that trees growing between the windrows had volumes of only about 73% that of trees growing on or within one meter of the windrow when plots were installed and about 81% from age 28 to 49. However, effect of tree position was not found to be significant for the post-redistribution period. The lack of difference may be confounded somewhat by varying numbers of

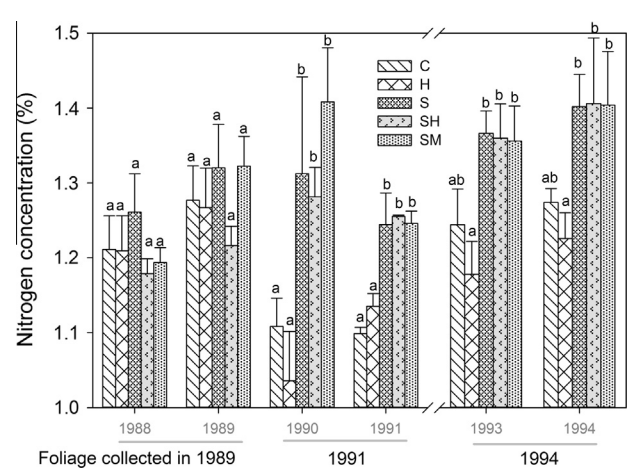

Fig. 4. Average nitrogen concentration (+1SE) of current and previous year ponderosa pine foliage collected when treatments were applied in 1989 and post-treatment in 1991 and 1994. C = control; H = understory hydroaxed to chips; S = windrows redistributed; SH = hydroaxed and windrows redistributed over chips; SM = understory removed manually and windrows redistributed. Bars with different letter within the same year indicate difference at $P < 0.05$.

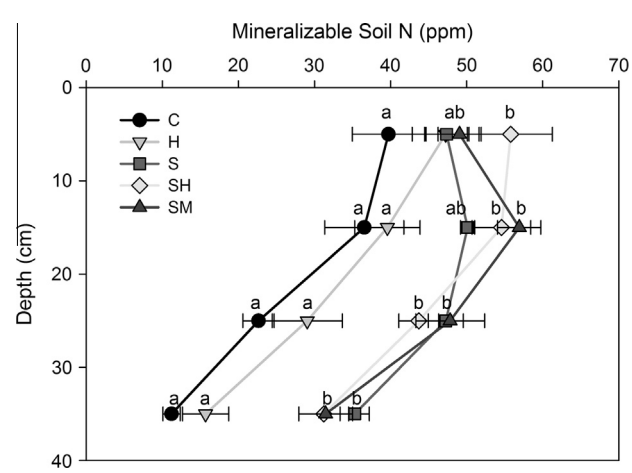

Fig. 5. Mean (±1SE) of soil mineralizable N at four depths among five treatments 1 year after treatments were applied in a 28-year-old ponderosa pine plantation. C = control; H = understory hydroaxed to chips; S = windrows redistributed; SH = hydroaxed and windrows redistributed over chips; SM = understory removed manually and windrows redistributed. Symbols with different letter within the same depth indicate difference at $P < 0.05$.

Table 2
Means and standard errors (kg ha^{-1}) of soil nitrogen and C/N ratio at four depths from various treatments in 1990 and 2010.

Year	Element	Depth (cm)	Treatment				
			C	H	S	SH	SM
1990	N (kg ha^{-1})	0–10	674.2 (69.6)a	768.2 (33.6)ab	938.8 (30.2)c	918.0 (19.2)bc	938.7 (52.7)bc
		10–20	631.5 (65.1)a	689.5 (44.2)ab	880.9 (30.0)c	799.5 (59.9)bc	849.9 (40.2)bc
		20–30	607.6 (69.9)a	639.6 (45.3)a	766.6 (39.4)a	729.9 (69.6)a	753.2 (51.3)a
		30–40	503.0 (54.2)a	528.0 (65.9)a	673.4 (40.6)a	616.1 (37.7)a	686.5 (64.0)a
	C/N ratio	0–10	22.6 (0.8)a	22.2 (0.3)a	22.0 (0.4)a	21.9 (0.3)a	18.6 (3.3)a
		10–20	19.5 (0.4)a	19.4 (0.4)ab	22.0 (0.3)c	21.9 (0.3)c	21.4 (0.4)bc
		20–30	17.8 (0.5)a	18.5 (0.4)ab	21.3 (0.3)c	20.1 (0.6)bc	19.9 (0.3)bc
		30–40	16.5 (0.4)a	16.9 (0.6)ab	19.4 (0.4)c	19.0 (0.3)c	18.7 (0.5)bc
2010	N (kg ha^{-1})	0–10	960.1 (70.0)a	957.1 (85.5)a	1270.4 (85.8)b	1108.5 (27.0)ab	1135.0 (52.4)ab
		10–20	1008.3 (97.1)a	1075.8 (33.1)a	1214.1 (76.8)a	1018.7 (86.4)a	1104.3 (72.0)a
		20–30	992.6 (117.6)a	1026.9 (86.5)a	1142.7 (108.7)a	962.3 (54.4)a	1096.8 (21.3)a
		30–40	1020.1 (63.7)a	981.6 (134.1)a	1084.5 (123.5)a	989.0 (47.2)a	1127.2 (42.1)a
	C/N ratio	0–10	19.7 (1.9)a	20.2 (2.2)a	15.6 (1.0)a	18.0 (0.8)a	18.4 (0.6)a
		10–20	19.7 (1.8)a	19.1 (0.4)a	16.3 (1.6)a	21.4 (1.4)a	19.0 (1.8)a
		20–30	21.8 (2.1)a	20.2 (1.9)a	17.6 (0.6)a	20.1 (2.2)a	14.8 (3.2)a
		30–40	20.9 (1.0)a	19.5 (0.6)a	20.3 (1.3)a	21.4 (0.3)a	19.2 (0.1)a

C = control; H = understory hydroaxed to chips; S = windrows redistributed; SH = hydroaxed and windrows redistributed over chips; SM = understory removed manually and windrows redistributed. Means with different letter within the same depth indicate difference at $P < 0.05$.

trees within windrow and between windrows among treatments after the thinning. In addition, it appears that trees in respread treatments have gained back some of the difference by their increased growth rate (moving from 73% to 81% in size), but have not closed the gap enough to separate these treatments from C and H.

Although the windrowing site preparation treatment is no longer used, at least on public lands in the western US, mitigating the displaced topsoil in existing windrowed plantations can be a challenge to earth scientists and foresters in forest restoration projects. Here, we found that redistributing topsoil significantly increased tree growth and stand development (Figs. 2 and 3). Understory shrubs were reduced and herbaceous species increased more quickly in the topsoil redistribution plots than in the control or H plots, suggesting improved plantation late-serial stage characteristics of a typical ponderosa pine dominant forest in the region (Smith, 1994). Furthermore, incidental root damage to established trees having roots in the windrows did not cause significant pathogen vectors leading to reduced growth or mortality (Table 1). Spread of root disease is a potential concern with practices such as subsoiling that disturb soils and established roots (Kliejunas and Otrosina, 1997; Otrosina et al., 2007).

Comparing tree growth results in H and S with C, trees in S significantly out-performed H in growth (Fig. 2). In fact, tree growth variables in S showed the highest among treatments. This result was not expected because competing vegetation had previously been reported as the most important factor for stand growth in the West (Haywood and Burton, 1989; Zhang et al., 2013). One likely explanation is that in the process of redistributing topsoil, much of the understory shrubs were incidentally uprooted, crushed and buried by the bulldozer, thereby reducing competing vegetation. This is supported by the results that understory biomass was much less in the S plots than in the control (Fig. 3A). However, redistributing 18 cm of topsoil also provided other benefits such as increased soil organic matter, increased supply of other nutrients in addition to N, improved soil microbial populations, redistributed grass seed that had lain dormant in the windrows, and provided an estimated 3–5 cm of added plant available water holding capacity back to the site. Some of these benefits were either directly or indirectly observed in this study, such as improved mineralizable N at all four depths (Fig. 5), and the lower C:N ratio by year 2010 (Table 2) which can be attributed to improved microbial action, increased herbaceous species (Fig. 3A), and the overall tree growth improvement (Fig. 2).

In summary, we found that about 18 cm of topsoil was windrowed, including 1.98 (±0.13) Mg N ha^{-1} and 41.04 (±2.46) Mg carbon ha^{-1}. These numbers are higher than have previously been reported. Trees within and close to windrows were about 36% larger in volume when plots were installed than trees between windrows; 21 years later they were still about 24% larger. In general, redistributing windrowed topsoil (S, SH, and SM) yielded a consistently positive effect on QMD, BA, and volume compared to C and H. No difference in growth was found between hydroaxed mastication (SH) and manual removal of shrubs (SM). The positive effects of shrub removal were evidenced only on the treatments without topsoil redistribution (C versus H); the difference in BA and volume between C and H was only significant in 1994. These results were supported by the higher soil nitrogen and mineralizable nitrogen content in the topsoil redistribution treatments than in the C or H treatment. Higher tree foliar nitrogen concentrations in the topsoil redistribution treatments further supported the higher tree growth rates there. Redistributing topsoil served to reduce the understory woody plant biomass while significantly enhancing herbaceous biomass six years after treatments were installed. These direct evidences further prove that windrowing site preparation where topsoil has been displaced reduces plantation growth and stand development. The negative effects can be mitigated by carefully redistributing windrowed topsoil back throughout the plantation.

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