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Mechanized Thinning, Prescribed Fire, and Needle Age Influences on the Mineral Nutrition of Jeffrey Pine: Elemental Concentrations in Foliage and Soil

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Abstract

Forest thinnings using cut-to-length and whole-tree harvesting approaches followed by prescription underburning were assessed for their influences over multiple growing seasons on the mineral nutrition of Jeffrey pine (*Pinus jeffreyi* Grev. & Balf.) on a Sierran site. Specifically examined were foliar and soil elemental concentrations encompassing macronutrients and micronutrients plus Al. Foliar N was higher in thinned stand subunits initially before transitioning to a relatively elevated concentration in the burned portion of either the cut-to-length or whole-tree subunits, while higher foliar S in the burned cut-to-length treatment combination was evident in the last two of the six sampling periods. Foliar Mn was usually higher in the burned whole-tree combination while B and Al were often higher in burned stand portions but with less specificity regarding thinning treatment. At mid growing season, N, P, K, S, Fe, and Cu were higher in young needles while Ca, Mn, and Al were so in older ones. Near mid study, mineral soil Ca was higher in the unthinned subunit while Mg, Fe, Mn, Zn, and Cu were higher in unburned stand portions.

Keywords: Forest nutrition; Tree nutrition; Soil nutrition; Density management; Wildland fire; Forest ecophysiology; *Pinus jeffreyi*

Introduction

With wildfire occurrence, intensity, and impacted acreage all on a rising trajectory in western USA forests [1-5] attributable to a host of developments that favor its proliferation, including detrimental alterations of stand composition and structure, excessive fuels accumulations, multiplying ignition sources, and climate change [3,5-17], natural resource managers are commonly being charged with implementing remedial measures that offer the potential to mitigate fire risk. To this end, an increasingly utilized fuels management practice is the application of thinnings accomplished through various manual and mechanized harvesting approaches, although demands for operational efficiency have resulted in a pronounced shift toward mechanization. Nevertheless, regardless of implementation approach, forest thinnings offer the benefits of reduced ladder and aerial fuels along with diminished canopy densities, factors that can lessen fire intensity and rates of spread. Aside from their potential to moderate wildfire behavior, however, thinnings also have the capacity to enhance overall stand health and vigor, in large part a reflection of their propensity to reduce the level of competition among residual stand constituents for scarce resources [18-21]. One manifestation of this involves the competition for mineral nutrients, and a generally held view is that nutrient supply per residual tree increases in approximate proportion to the reduction in stocking [22], suggesting that post-thinning expansion of tree root systems may permit enhanced nutrient uptake by residual stems. Other factors in post-thinning stand nutrition include the potential for diminished canopy density to result in increases in the average temperature and moisture content of the forest floor, which in turn may elevate mineralization rates and therefore nutrient supply, although if the harvesting approach involves the retention of substantial slash deposits within the stand, nutrient immobilization by microbes may negate any gains in such supply [23]. Similarly, increased sunlight on the forest floor may stimulate development of shrub understories, which when present in western USA forests often include N fixing species [21], but given sufficient development, shrub understories may also compete with the residual tree stand for other nutrients. Given the growing perception that thinnings are a necessary component of comprehensive wildfire mitigation programs in forested regions, which is likely to expand their use considerably, understanding their impacts beyond that of altering fire behavior, such as those on stand nutrition, is warranted in order to assess their overall forest health ramifications.

Prescribed fire, in the form of underburning, is also an increasingly relied upon wildfire mitigation practice in western USA forests, in some instances implemented alone but more often in tandem with overstory thinning. It is viewed as particularly appropriate in forest cover types that previously experienced frequent, low-to-moderate severity surface fires where it may facilitate the restoration of historic stand characteristics that impart greater resistance and resilience to stand-replacing crown fires [10,21,24-27], particularly regarding reductions in surface and ground fuel loading. However, aside from its role in fuels management, the use of prescribed fire has implications for stand nutrition as well, although its impacts on nutrient availability are sufficiently varied to render generalizations questionable. Nevertheless, at the low-to-moderate fire intensities assumed to produce the most commonly desired outcomes, immediate N, P, and base cation availability is generally thought to increase while decreased soil acidity may reduce that of metallic elements, but the longevity of these effects is uncertain [22,28,29]. Perhaps the most critical factor influencing whether increased post-fire nutrient availability proves to be ultimately meaningful in terms of increased uptake by stand constituents is the impact on their fine root fraction and associated mycorrhizae, as these nutritionally vital root system components may suffer some loss where localized fire intensities and/or residence times, which typically vary across the acreages involved in an underburn, are higher [22,29-31]. As the ultimate indicator of the fertility of any forest site, including those subjected to controlled underburns, resides in the amounts of nutrients contained in the vital tissues of stand constituents relative to the biomass therein, assessments of elemental concentrations in such tissues are a critical component of attempts to ascertain overall stand nutritional status that has been little studied in evaluations of prescribed fire effects on forest vegetation.

The study presented here involved an examination of foliar and soil nutrition in an eastern Sierra Nevada Jeffrey pine stand as influenced by mechanized thinning accomplished through two widely divergent harvesting approaches and followed by prescribed fire. Specifically determined were elemental concentrations in foliage over multiple post-treatment growing seasons accompanied by a mid-study assessment of the same in the soil, all of which was augmented by measurements of mensurational, fire injury, and site features. Regression analysis was utilized to discern relationships between nutrition and selected stand, individual tree, and site variables for purposes of evaluating the factors influencing the former.

Materials and Methods

Study site

Located on the Truckee Ranger District of the Tahoe National Forest, the eastern Sierran site upon which this study was conducted consists of 12.1 ha at an elevation of 1800 m with a generally northeast aspect (39°25′45″N, 120°8′30″W). The slope varies from 3 to 12% but most of the site falls within 3 to 6%. Average annual precipitation is 69 cm based on 55-year records and is predominantly snowfall. Precipitation for the year in which this study commenced was only 30 cm, a total that was 43% of the long-term average, while it was 49 cm in the second year and 58 cm in the third year, which was 71% and 84%, respectively, of the average. The soils are of the Kyburz-Trojan complex [32] and are well drained with a gravelly sandy loam surface layer and an andesitic substratum, while the site quality is SI 10021 (index height in meters) for Jeffrey pine [33].

Treatment installation

Following the conclusion of the growing season immediately prior to that during which this study commenced, the site was divided into three subunits of equal proportion with one of three thinning treatments randomly assigned to each subunit, specifically a cut-to-length harvesting system, a whole-tree harvesting system, or an unthinned control. As reviewed by Walker et al. [34], cut-to-length and whole-tree systems vary greatly in their harvesting approach and site impacts. The former system utilizes two machines, one which processes the trees at the stump, thereby creating residual organic materials that it concentrates into slash mats, while the second machine self-loads the logs and forwards them to a landing. Both machines travel over the slash mats, minimizing the exposure and compaction of mineral soil, but the mats also constitute elongated surface fuel concentrations. Whole-tree harvesting systems involve two machines as well, one of which fells selected trees and bunches them for transport while the second machine skids them to a landing where further processing ensues. All organic residues created by the harvest are extracted from the stand, reducing wildfire risk but also exposing mineral soil and increasing associated impacts. The thinning treatments were implemented concurrently using a Timberjack 1270 processor combined with a Timberjack 1210 forwarder (Timberjack Forestry Group, Moline, IL, USA) for the cut-to-length system while the whole-tree system used a Timbco 445 feller-buncher (Timbco Hydraulics, Inc., Shawano, WI, USA) and a Caterpillar 518 grapple skidder (Caterpillar, Inc., Peoria, IL, USA). For both treatments, a free thinning approach [20] was followed to release select dominant and codominant crown class trees that displayed good growth form and crown development. Trees that were removed varied in crown class but few were < 25.4 cm DBH and those < 20.3 cm DBH were intentionally felled only when they posed an obstacle to the harvesting operation.

At the onset of the growing season immediately following that during which the study commenced, a prescribed under burn was implemented on one half of each of the three subunits dedicated to the individual thinning treatments. The subunits were divided by 1.0-m-wide hand lines and one of the two portions of each subunit was randomly designated to be burned while the other was to remain unburned. For those to be burned, a strip head fire ignition pattern was applied beginning at 6:00 p.m. with the treatment of all three portions completed by 11:00 p.m. of the same day. At the time of ignition the air temperature was 16°C, relative humidity was 48%, and the wind speed was 5.5 km hr^{-1}, with variation over the course of the 5 hr burn period ranging from 14 to 18°C, 39 to 50%, and 4.8 to 6.6 km hr^{-1}, respectively. The fuel moisture content was 8% for 1 hr, 10% for 10 hr, 14% for 100 hr, and 25% for 1000 hr time lag categories. The average rate of spread of the prescribed fire was approximately 58 m hr^{-1} and the average flame length was approximately 0.7 m.

Vegetation and fuels measurements

Immediately prior to thinning treatment implementation, 30 permanent 0.08 ha circular plots were established for measurement of mensuration variables with 10 plots located in each of the three subunits, and within each subunit, five in the portion to be burned with the remaining five in the portion to remain unburned. At the initial inventory, all trees ≥ 10.2 cm DBH within these plots were measured for total height, DBH, and live crown length and then tallied by species. Because of prior marking of the trees to be harvested in the subunits to be thinned, marked trees were also tallied as such. Subsequently, tree heights and live crown lengths were used to calculate live crown percentages, and average DBH values by plot were calculated using the quadratic mean formula [35]. Basal area by plot was derived from quadratic mean DBH in combination with plot stem counts [36], and because the trees to be harvested in the thinned subunits were known, the pending residual density of pertinent plots was determined in like manner. This inventory also included standing dead trees that were identified as those lacking any live crown, which was used to determine live tree count and percentage. Ultimately, the total tree count, basal area, and live tree count for each plot were expanded to reflect equivalent 1.0 ha values. From among unmarked trees, designation and coring (4.3-mm cores extracted 1.37 m above ground) of one live Jeffrey pine site tree per plot of dominant or codominant crown class and good growth form permitted the determination of the age and radial growth rate of stems with crowns constituting the upper canopy levels of the over story. Total age was determined by counting the late wood rings from pith to phloem and adding 10, the latter an approximation of the average number of years required for Sierra Nevada conifers to reach sufficient size to produce their first countable ring at breast height [37]. Growth rate was determined by counting the rings in the outermost 2.54 cm of each core. A second inventory identical to that detailed above in every respect was conducted at the conclusion of the final growing season included in the study and all extrapolated values regarding tree dimensions, density, and mortality were again calculated, but at this inventory additional variables were quantified. Specifically, bole char height was measured and ultimately expressed on an absolute basis and as a percentage of tree height, and the average charred percentage of the circumference of the bole extending throughout the char height was estimated with periodic calibration by direct measurement at a constant height interval on randomly selected trees. Furthermore, plot biomass for individual above-ground tree components, specifically foliage, branch, bole bark, and bole wood, was calculated from DBH measurements using the species-specific formulas of Gholz et al. [38], and these quantities were then expressed by plot as the total of all components combined across species, with all plot values ultimately expanded to reflect equivalent 1.0 ha values. As they reflect imposed treatment influences, measurements and derived values from the second inventory are of principal importance for the purposes of this study.

Concurrent with the second inventory of cover story vegetation, an inventory of the shrub and herbaceous understory vegetation occupying the site was conducted. This was based on 54 m^2 circular plots established with the same centers as those for the 0.08 ha plots noted above which were used for the mapping to scale of individual understory species, thus permitting the expression of the prevalence of such species on a percent ground cover basis. Pertinent specifically to the study reported here, the cover by all species in total was then determined.

Also concurrent with the second over story inventory was one of downed and dead fuels, which entailed measurements by individual time lag category except for those designated as fine fuels, specifically the 1 hr and 10 hr categories, which were combined. For the 1+10 hr (≤ 2.5 cm diameter) fuels, duff, litter, and fine woody debris from 10 randomly located circular plots of 0.049 m^2 each within each of the 0.08 ha plots were collected, dried to a constant weight, and weighed. The dry weights of each group of 10 samples were then averaged. For coarse fuels, specifically the 100 hr (> 2.5 to ≤ 7.6 cm diameter) and 1000 hr (> 7.6 cm diameter) categories, a single 4 m^2 and single 54 m^2 circular plot, respectively, was established with the same plot center as that of each of the 0.08 ha plots. Collection of the 100 hr fuels from the 4 m^2 plots permitted a dry weight determination by direct measurement as well. For 1000 hr fuels, however, lengths and the diameters at mid length were measured for use in the calculation of an estimate of volume according measuring their dimensions, and then drying and weighing them provided a density constant for use in converting volume to dry weight by plot. Ultimately, all fuel weights were expanded to reflect equivalent 1.0 ha values, and fine fuel and coarse fuel weights were also combined to determine total fuel loading.to the Huber formula [39]. Collection of 10 log sections from random locations outside the plots.

Foliar and soil analyses

Assessments of foliar nutrition were conducted in six sampling periods, hereafter designated Period 1 through 6, distributed over multiple growing seasons. Specifically, the Period 1 sampling was conducted in late August of the first season of the study, which was the growing season following the implementation of the thinning treatments but before that during which the prescribed fire was; those of Period 2 and Period 3 were conducted in late May and late August, respectively, of the second study season with the former occurring soon after implementation of the prescribed fire; and those of Period 4, Period 5, and Period 6 were conducted in late May, early July, and late August, respectively, of the third and final study season. Thus, over three successive years, foliar sampling was conducted during the late, early and late, and early, middle, and late growing season, respectively. During each sampling period, fully elongated needle subsamples were severed from two small boughs selected from the middle one-third portion of the crowns of each of the 30 site trees, as had been designated during the initial stand inventory, and combined into one composite sample per tree. Any needles exhibiting visible injury were discarded at collection. Because fully elongated needles were collected for analysis at every sampling, these constituted the needles of the previous year when collected during the early and middle growing season but constituted current year needles when collected during the late season. For Period 5 only, additional samples were collected from each tree consisting of current year but partially elongated needles, with their elongation at approximately 60% for this sampling. These samples permitted an assessment of the influence of needle maturity on foliar nutrition. Ultimately, all samples were dried at 75°C for 24 hr, ground to pass a 20-mesh (850-μm opening) screen, and then analyzed for total N using a Leco Model FP428 N Analyzer (Leco Corp., St. Joseph, MI) and for P, K, Ca, Mg, S, Fe, Mn, Zn, Cu, B, and Al by inductively coupled plasma (ICP) spectroscopy after wet ashing with HNO3 and HClO4 [40].

For purposes of characterizing the soil near the site trees, 10 subsamples were collected to a depth of 20 cm in mineral soil from random locations within the confines of each plot and combined into one composite sample per plot for a total of 30 composite samples. This sampling coincided with the Period 3 foliar sampling, and thus occurred near the midpoint of the study. All soil samples were air dried for 30 days, sieved to pass a No. 10 (2.0-mm opening) screen, and analyzed as follows: texture by the hydrometer method; organic matter by loss on ignition; pH by glass electrode on a 1:1 mixture (by weight) of soil and distilled water; total N using a Leco Model FP428 N Analyzer (Leco Corp., St. Joseph, MI); P1 (Bray 1) and P2 (Bray 2) colorimetrically after extraction with NH4F and HCl; K, Ca, Mg, and S by ICP spectroscopy after extraction with NH4C2H3O2; Fe, Mn, Zn, Cu, and B by ICP spectroscopy after extraction with HCl; and Al by ICP spectroscopy after extraction with KCl [41,42].

Statistical anaylses

Field logistics involving the implementation of the thinning and prescribed fire treatments necessitated that the thinning treatments be assigned to individual stand subunits with the underburn then assigned to one half of each subunit. Consequently, it was necessary to test for the independence of the plots within each thinning and fire treatment combination using initial data for variables germane to this study. The chosen variables were tree height, DBH, live crown length, basal area, and total stem count. For each variable, residual values were calculated, which were defined as the difference between the mean for a given variable of the five plots of each treatment combination and the values obtained from the individual plots for the selected variable. Subsequently, the residual value of one plot was designated as the independent variable and that of the immediately adjacent plot the dependent variable which was repeated sequentially within each treatment combination, yielding one value of each for each plot pair, four values of each for each of the six treatment combinations, and a total of 24 values of each for the entire stand. These values were then incorporated into simple linear regression models by variable. For each regression, models were considered to be significant, signifying a lack of independence among the plots within treatments, only when $p \leq 0.05$ according to the F test. None of the models proved to be significant, indicating that values from individual plots were not significantly influenced by those from immediately adjacent plots for any of these variables.

Data pertaining to foliar nutrition as reflected in the samples of fully elongated needles were analyzed using repeated measures, mixed model analysis of variance (ANOVA) to test for effects of the thinning and prescribed fire treatments plus that of sampling period along with all possible interactions. This analysis incorporated both the compound symmetry covariance structure and the first-order autoregressive structure. For each variable, the covariance structure relied upon was that providing the lowest value for Akaike's Information Criterion (bias-corrected version, AICC). For foliar nutrition data that pertained to samples of partially elongated as well as those of fully elongated needles, 3-way ANOVA was used to assess the effects of thinning and fire treatments plus needle year along with all possible interactions. Data concerning soil physical and chemical characteristics were analyzed using two-way ANOVA to test for thinning and fire treatment effects plus their interaction, and those concerning stand biomass and the mensurational and fire injury characteristics of the site trees were also analyzed using this approach. In every ANOVA indicated above, the arcsine transformation was performed on all percentage data, and main and interaction effects were considered significant only when $p \leq 0.05$ according to the F test. Subsequently, differences among means were evaluated using the least significant difference (LSD) test with $\alpha=0.05$. Regarding analyses of the other data incorporated into this study, consult Walker et al. [43] for those concerning the initial stand level mensurational features derived from the first inventory, Walker et al. [44] for those involved with the final stand level mensuration and fire injury characteristics as quantified in the second inventory, Salverson et al. [45] for understory vegetation data, and Swim et al. [46] for those concerned with downed and dead fuels.

Additional statistical analysis consisted of two series of simple linear regression models used to investigate relationships between variables selected as particularly pertinent to the nutrition of the subject stand, specifically with the first series dedicated to foliar nutrition and the second to that of the soil. In both series, all models incorporated values derived from each of the 30 site trees or from the plots associated with them as appropriate. Due to the extensive array of variables examined in the first series, it was divided into five subsets, hereafter denoted the mensuration, fire injury, understory vegetation, forest floor fuels, and soil influences subsets. The mensuration subset consisted of models incorporating all possible combinations of post-treatment site tree height, DBH, and live crown length and percentage, pretreatment site tree age and growth rate, and post-treatment stand basal area, total and live tree counts, and total biomass as the independent variables with the individual foliar elemental concentrations of each sampling period serving as dependent variables. The fire injury subset incorporated all possible combinations of bole char height, expressed on both absolute and percentage bases, and char circumference of the site trees as independent variables with the same array of dependent variables noted above except that values derived from Period 1 samples were excluded, reflecting that the fire treatment had not yet been implemented at the time of their collection. For the understory vegetation and forest floor fuels subsets, post-treatment percent total ground cover and downed and dead fuels by timelag category and in total, respectively, served as independent variables while the complete array of foliar nutrition values again constituted the dependent variables. In the fifth subset of the first series, the soil concentration of each element was designated the independent variable and that of the same element in the foliage was the dependent variable. The second regression series entailed models incorporating all possible combinations of post-treatment basal area and total and live tree counts, total biomass, percent total ground cover, downed and dead fuels by timelag category and in total, and soil textural percentages and pH as the independent variables while soil organic matter and elemental concentrations served as dependent variables. In each of the two series and all subsets therein, regression models were considered significant only when $p \leq 0.05$ according to the F test. All statistical analyses were performed using SAS (SAS Institute, Inc., Cary, NC).

Results

Stand, understory, and fuels characteristics

The stand under study consisted of 97% Jeffrey pine and 3% California white fir (*Abies concolor* var. lowiana [Gord.] Lemm.) at the initial inventory with an overall mean height of 15.1 m, mean DBH of 32.5 cm, and a mean live crown length and percentage of 8.1 m and 53%, respectively. Pretreatment basal area averaged 30.2 m^2 ha^{-1} distributed over an average of 407 trees ha^{-1} of which 397 trees ha^{-1}, amounting to 97.6%, were live stems. The pending residual basal area across all plots to be thinned averaged 16.7 m^2 ha^{-1} dispersed over 304 stems ha^{-1}. Pretreatment characteristics of this stand are presented in greater detail in Walker et al. [43]. The Jeffrey pine component of the stand declined marginally to 96% with that of white fir increasing to 4% at the second inventory. Overall mean height, DBH, and live crown length and percentage at this inventory was 15.1 m, 32.9 cm, 7.7 m, and 48%, respectively, with a significantly greater tree height in the burned portion of the unthinned subunit and lesser ones in burned portions of both the cut-to-length and whole-tree subunits, and a larger DBH in the unburned and burned portions of the whole-tree and unthinned subunits, respectively, than in the burned portions of the cut-to-length and whole-tree subunits. Among notable disparities regarding live crown, significantly greater lengths were found in the unburned than in the burned portions of both the cut-to-length and whole-tree treatments and greater percentages prevailed in the unburned than burned portions within all three thinning treatments. Of the fire injury indicators quantified at the second inventory, bole char height expressed on absolute and percentage bases was 1.9 m and 15.7%, respectively, when averaged across burned stand portions, with significant disparities limited to those between the two fire treatments regarding the former but with additional ones between higher values in the burned portions of the cut-to-length and whole-tree subunits and a lesser one in the burned portion of the unthinned treatment for the latter. Bole char circumference was 41.6% when averaged across burned stand portions and also exhibited a significant disparity other than those between fire treatments, specifically a higher percentage in the burned portion of the whole-tree subunit than in the burned portion of the unthinned subunit. For the two stand density measures at the second inventory, basal area averaged 21.4 m^2 ha^{-1} across all treatments with the difference between a higher value in the unburned and unthinned treatment combination and a lower one in the unburned whole-tree combination constituting the only significant disparity, while the overall total tree count averaged 283 stems ha^{-1} with the lone significant difference consisting of that between a higher count in the burned cut-to-length combination and a lower one in the unburned whole-tree combination. Live tree count averaged only 240 stems ha^{-1}, however, amounting to 84.8% of the total, with the lowest live percentage found in the burned whole-tree combination which was significantly less than that in the burned cut-to-length combination, which in turn was significantly less than those prevailing in all remaining treatment combinations. Post-treatment characteristics of this stand are presented in greater detail in Walker et al. [44].

Enumerated by treatment in the order of the cut-to-length burned, cut-to-length unburned, whole-tree burned, whole-tree unburned, unthinned burned, and unthinned unburned combinations, mean total post-treatment biomass, as quantified at the second inventory, was 71412, 84559, 76496, 79864, 86690, and 99353 kg ha^{-1}, respectively. According to ANOVA, the only significant effect imposed on this variable was that of the thinning × fire treatment interaction (p=0.0498). Accordingly, the LSD test identified as significant the difference between the highest value in the unburned portion of the unthinned subunit and the lowest one in the burned portion of the cut-to-length subunit.

The understory community on the study site was dominated by an array of shrubs, most prominently antelope bitterbrush (*Purshia tridentata* [Pursh] DC.) and mahala mat (*Ceanothus prostratus* Benth.), with grasses and forbs constituting only minor components. Averaged across all treatments, total ground cover at the conclusion of the study was 10.9%, with the highest cover found in the unburned portion of the unthinned subunit and the least in the burned portion of the whole-tree subunit. Indicative of the paramount influence the under burn exerted on understory abundance, total cover in the unburned stand portions was 5.8x that in burned portions when averaged across the three thinning treatments. The understory vegetation at this site is quantified in greater detail in Salverson et al. [45].

When averaged across all treatments, downed and dead fuel loading at the conclusion of the study was 47408 kg ha^{-1} for the 1+10 hr time lag categories, 6252 kg ha^{-1} for the 100 hr category, 6200 kg ha^{-1} for the 1000 hr category, and 59860 kg ha^{-1} for total fuels. The unburned portion of the cut-to-length subunit had the greatest 1+10 hr loading which significantly exceeded not only that in the burned portion of the unthinned subunit, which had the lowest overall, but also those in all of the remaining treatment combinations. The unburned portion of the cut-to-length subunit had the greatest overall 100 hr and 1000 hr loading as well, which for the former significantly exceeded those in the burned portions of all three thinning treatments along with that in the unburned portion of the unthinned treatment, while for the latter it exceeded that in the unburned portion of the whole-tree subunit plus those in both portions of the unthinned subunit. Regarding the 100 hr and 1000 hr categories, the burned portion of the unthinned treatment exhibited the least loading overall. With its supremacy in each of the individual time lag categories, the unburned portion of the cut-to-length treatment exhibited the greatest total loading by default which significantly exceeded the totals in all of the remaining treatment combinations, while the lowest total overall was once again found in the burned but unthinned combination. Further details about the downed and dead fuel loading at this site are reported in Swim et al. [46].

Site tree characteristics

For the Jeffrey pine site trees utilized in the assessments of foliar nutrition, ANOVA identified all main and interaction effects to be non-significant for height, DBH, age, and growth rate (Table 1). In similar manner, the LSD test disclosed no significant differences among the various treatment combinations regarding all but the latter of these variables for which it indicated that the rate in the burned whole-tree combination was exceeded by those in the burned and unburned cut-to-length combinations and the burned but unthinned combination. Regarding live crown, ANOVA revealed a significant fire treatment effect for live length (p = 0.0365) and thinning × fire treatment interaction effects for this (p = 0.0310) and live percentage (p = 0.0036), with the LSD test disclosing a significantly shorter length in the burned but unthinned combination than in all others and a lower percentage in the former than in all others except the unburned whole-tree combination along with a lesser percentage in the latter than in the unburned cut-to-length and unthinned combinations. Predictably, the only site trees to exhibit bole char were those located in burned stand portions, thus the significant fire treatment effects revealed by ANOVA on bole char height (p = 0.0006), height percentage (p = 0.0003), and circumference (p < 0.0001) were matched with disparities denoted as significant by the LSD test between burned and unburned treatments within every thinning treatment. Within the burned treatment, however, this test also deemed as significant differences between higher values in the cut-to-length treatment and lower ones in the unthinned treatment for char height and height percentage.

Thinning and fire treatment	Height (m)	DBH (cm)	Live crown (m) (%)		Bole char height (m) (%)		Bole char circumference (%)	Age (yrs)	Growth rate (rings cm^{-1})
Cut-to-length									
Burned	21.3a	41.7a	12.7a	60ab	2.1a	10a	26a	112a	6.5b
Unburned	20.6a	42.5a	13.7a	66a	0.0c	0c	0b	103a	6.4b
Whole-tree									
Burned	21.8a	43.4a	13.3a	62ab	1.3ab	6ab	34a	102a	9.1a
Unburned	23.6a	49.4a	12.7a	54bc	0.0c	0c	0b	104a	6.7ab
Unthinned									
Burned	20.7a	43.9a	10.2b	49c	0.8b	4b	24a	106a	6.2b

Unburned	20.5a	39.9a	14.2a	69a	0.0c	0c	0b	101a	7.1ab

Table 1: Mensurational and Fire Injury Characteristics of Site Trees in a Pure, Uneven-Aged Jeffrey Pine Stand as Influenced by Mechanized Thinning and Prescribed Fire.[1]

[1]Within each variable, means sharing a common letter do not differ significantly at $\alpha = 0.05$ according to the LSD test; each mean was derived from post-treatment measurements of five trees (n = 5) of dominant or codominant crown class.

Elemental concentrations in fully elongated needles

ANOVA revealed multiple influences to be significant regarding foliar N in the site trees, specifically those of the fire treatment ($p = 0.0240$), sampling period ($p < 0.0001$), and the thinning treatment × sampling period ($p = 0.0193$) and thinning treatment × fire treatment × sampling period ($p = 0.0485$) interactions (Table 2). Significant differences among treatments as designated by the LSD test were also numerous, consisting of those between higher concentrations in the burned portion of the cut-to-length subunit and lower ones in the unthinned subunit irrespective of fire treatment and others concerning the higher N of trees in the unburned portions of the cut-to-length and whole-tree subunits than that found in the unthinned and unburned combination for Period 1. For Period 2, such disparities involved higher concentrations in the burned portions of the cut-to-length and whole-tree subunits than that in the unthinned and unburned combination. In Period 3, significantly higher N was found in trees of the burned whole-tree combination than in those of the unburned portions of the cut-to-length and whole-tree subunits, while in Period 4 N was higher in the former than in either portion of the cut-to-length subunit. Significant differences in Period 5 consisted of a higher concentration in the burned portion of the cut-to-length treatment than those in the unburned portions of this and the whole-tree treatments along with higher ones in burned portions of the whole-tree and unthinned treatments than that in the unburned whole-tree combination. Lastly, N concentrations were significantly higher in the burned portion of the whole-tree treatment and unburned portion of the unthinned treatment than in the unburned and burned portions of the cut-to-length and unthinned treatments, respectively, for Period 6. The sampling period influence indicated by ANOVA for foliar N was manifested in a lower average concentration in Period 5 than those prevailing at the other samplings. The sole influence disclosed by ANOVA regarding foliar P was that of sampling period ($p < 0.0001$), and its concentrations were higher overall in Period 3 and 6 than at the other samplings. Despite the lack of other influences denoted by ANOVA, however, the LSD test identified the P concentration in Period 3 of trees residing in the burned portion of the whole-tree treatment as significantly exceeding that of the trees in the unburned portion of the cut-to-length treatment. Along with sampling period ($p < 0.0001$), significant effects disclosed by ANOVA on foliar K were those of thinning treatment ($p = 0.0195$) and the thinning × fire treatment interaction ($p = 0.0500$), while some of the treatment combinations were differentiated by the LSD test at every sampling. For Period 1, it denoted the higher K in both portions of the cut-to-length subunit plus that in the unburned portion of the whole-tree subunit as significantly exceeding the concentration in the unthinned and unburned combination, and in Period 2 it did so regarding higher ones in the unburned portions of the cut-to-length and whole-tree subunits plus that in the burned portion of the unthinned subunit compared to the latter. Period 3 differences amounted to significantly higher concentrations in the whole-tree subunit irrespective of fire treatment than in all remaining treatment combinations, while those in Period 4 consisted of higher ones in the unburned portions of the cut-to-length and whole-tree subunits than in the burned portion of the former and the unburned portion of the unthinned subunit along with a higher one in the unthinned but burned combination than in the burned cut-to-length combination. In Period 5, the lone significant difference consisted of that between a higher K in the unthinned but burned treatment and a lower one in the burned cut-to-length combination, while higher K in the unburned portion of the whole-tree treatment than in the burned portion of the cut-to-length treatment and either portion of the unthinned treatment constituted such differences in Period 6. The sampling period influence on foliar K indicated by ANOVA was evident in lower overall concentrations in Period 2 and 4 than in the remaining periods.

Sampling period	Thinning and fire treatment	Macronutrient concentration (%)						Micronutrient concentration (µg g^{-1})					
		N	P	K	Ca	Mg	S	Fe	Mn	Zn	Cu	B	Al (µg g^{-1})
1	Cut-to-length												
	Burned	1.15a	0.10a	0.52a	0.31b	0.11ab	0.07a	65ab	189abc	27a	2.4a	23a	171a
	Unburned	1.11ab	0.09a	0.51a	0.36ab	0.12ab	0.06ab	73a	225ab	36a	3.0a	19abc	154ab
	Whole-tree												
	Burned	1.09abc	0.09a	0.46ab	0.35ab	0.10b	0.06ab	65ab	256a	30a	2.4a	21ab	181a
	Unburned	1.11ab	0.10a	0.54a	0.31b	0.12ab	0.06ab	68ab	127c	31a	2.8a	14c	106b
	Unthinned												

	Burned	1.04bc	0.09a	0.45ab	0.32b	0.10b	0.05b	52b	124c	27a	2.4a	19abc	102b
	Unburned	1.01c	0.08a	0.37b	0.47a	0.13a	0.05b	62ab	156bc	31a	2.4a	16bc	103b
2	**Cut-to-length**												
	Burned	1.16a	0.09a	0.33ab	0.23b	0.10a	0.06a	158b	176ab	20ab	4.2ab	13a	153a
	Unburned	1.11ab	0.10a	0.36a	0.30ab	0.10a	0.06a	71c	178ab	29a	5.2a	13a	126ab
	Whole-tree												
	Burned	1.13a	0.09a	0.35ab	0.30ab	0.10a	0.06a	162b	230a	27ab	4.0b	15a	162a
	Unburned	1.08ab	0.09a	0.38a	0.33ab	0.10a	0.06a	161b	172ab	29a	4.6ab	12a	99b
	Unthinned												
	Burned	1.09ab	0.09a	0.36a	0.24b	0.10a	0.06a	281a	128b	19b	4.4ab	14a	125ab
	Unburned	1.01b	0.08a	0.29b	0.37a	0.11a	0.06a	141b	160ab	23ab	4.8ab	13a	86b
3	**Cut-to-length**												
	Burned	1.03ab	0.13ab	0.43b	0.18b	0.10a	0.06a	78ab	142ab	26a	3.8a	16ab	112ab
	Unburned	0.92b	0.10b	0.45b	0.27a	0.09a	0.05a	106a	183a	29a	3.6a	16ab	130a
	Whole-tree												
	Burned	1.12a	0.14a	0.55a	0.24ab	0.10a	0.06a	83ab	139ab	29a	4.2a	18a	140a
	Unburned	0.97b	0.11ab	0.59a	0.24ab	0.09a	0.06a	96a	112b	27a	4.0a	14b	97ab
	Unthinned												
	Burned	1.02ab	0.12ab	0.45b	0.19b	0.08a	0.06a	61b	95b	24a	3.0a	18a	69b
	Unburned	1.04ab	0.12ab	0.45b	0.24ab	0.10a	0.05a	55b	96b	29a	2.8a	16ab	67b
4	**Cut-to-length**												
	Burned	0.94b	0.08a	0.24c	0.19b	0.10a	0.04a	67a	120bc	28ab	2.2a	11ab	81bc
	Unburned	0.94b	0.09a	0.32a	0.30a	0.10a	0.05a	56a	190ab	34a	2.4a	13ab	106ab
	Whole-tree												
	Burned	1.06a	0.09a	0.29abc	0.30a	0.09a	0.05a	64a	206a	31ab	3.0a	14a	134a
	Unburned	1.00ab	0.09a	0.33a	0.27ab	0.10a	0.05a	81a	145abc	35a	2.2a	10b	61c
	Unthinned												
	Burned	1.04ab	0.08a	0.30ab	0.24ab	0.08a	0.05a	58a	109c	25b	2.2a	12ab	73bc
	Unburned	1.03ab	0.09a	0.25bc	0.28ab	0.10a	0.05a	42a	115c	30ab	3.0a	12ab	46c
5	**Cut-to-length**												
	Burned	0.86a	0.10a	0.41b	0.24b	0.11a	0.11a	62b	161b	24c	2.6b	13bc	120ab
	Unburned	0.71bc	0.10a	0.49ab	0.30ab	0.11a	0.06b	53b	181ab	32ab	5.6a	13bc	92ab
	Whole-tree												
	Burned	0.84ab	0.10a	0.47ab	0.35a	0.11a	0.06b	63b	238ab	33ab	4.0b	18ab	133a

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	Unburned	0.67c	0.11a	0.50ab	0.29ab	0.11a	0.06b	95a	145b	38a	3.8b	11c	97ab
	Unthinned												
	Burned	0.83ab	0.11a	0.55a	0.37a	0.10a	0.06b	46b	323a	25bc	3.8b	20a	127a
	Unburned	0.81abc	0.09a	0.43ab	0.34ab	0.11a	0.05b	70ab	167b	33ab	3.8b	13bc	68b
6	**Cut-to-length**												
	Burned	1.03ab	0.13a	0.51b	0.27a	0.10a	0.08a	48ab	170ab	22b	2.8b	14a	134a
	Unburned	0.96b	0.12a	0.56ab	0.22a	0.10a	0.07ab	50ab	146b	28ab	3.8a	15a	76ab
	Whole-tree												
	Burned	1.14a	0.13a	0.58ab	0.24a	0.10a	0.07ab	41b	219a	29ab	4.0a	16a	128a
	Unburned	0.97ab	0.12a	0.63a	0.28a	0.11a	0.06b	42b	145b	33a	3.2ab	12a	67ab
	Unthinned												
	Burned	0.93b	0.10a	0.51b	0.25a	0.10a	0.06b	65a	126b	32a	3.6ab	17a	65b
	Unburned	1.14a	0.12a	0.51b	0.27a	0.12a	0.07ab	48ab	139b	35a	3.4ab	16a	60b

Table 2: Foliar Concentrations of Nutrients and Al in Site Trees of a Pure, Uneven-Aged Jeffrey Pine Stand as Influenced by Mechanized Thinning and Prescribed Fire.[1]

[1]Within each combination of element and sampling period, means sharing a common letter do not differ significantly at $\alpha = 0.05$ according to the LSD test; each mean was derived from concentrations in fully elongated needles of five trees (n = 5) of dominant or codominant crown class. [2]Prescribed underburn not yet implemented.

Of the other macronutrient concentrations, that of Ca was significantly affected by fire treatment (p=0.0247) and sampling period (p<0.0001) according to ANOVA, while the LSD test disclosed significant differences among some treatments in all except the last sampling period (Table 2). Specifically, the concentration in the unburned and unthinned combination exceeded those in the burned portions of the cut-to-length and unthinned subunits and in the unburned portion of the whole-tree subunit in Period 1, and with the exception of the latter, did so again in Period 2. In Period 3, Ca in the unburned portion of the cut-to-length subunit exceeded the concentrations in the burned portions of this and the unthinned subunits, while in Period 4, Ca in the unburned and burned portions of the cut-to-length and whole-tree subunits, respectively, surpassed that in the burned portion of the former, and in Period 5, concentrations in the burned portions of the whole-tree and unthinned subunits surpassed that in the burned cut-to-length combination. The sampling period influence on Ca indicated by ANOVA was largely evident in lower concentrations on average in Period 3 and 6 than in the remaining periods. Foliar Mg concentrations were influenced by sampling period ($p < 0.0001$) and by the fire treatment × sampling period interaction ($p = 0.0331$) according to ANOVA, with the former manifested in somewhat lower concentrations overall in Period 3 and 4 and the latter largely confined to Period 1 when the LSD test revealed the differences between a higher concentration in the unthinned and unburned combination and lower ones in the burned portions of the whole-tree and unthinned treatments to be significant. Consisting of the thinning ($p = 0.0264$) and fire ($p = 0.0287$) treatment, sampling period ($p < 0.0001$), and the thinning treatment × sampling period ($p = 0.0022$), fire treatment × sampling period ($p = 0.0006$), and thinning treatment × fire treatment × sampling period (p=0.0295) interaction effects, a wider array of influences was deemed significant by ANOVA on S than that prevailing for any other elemental concentration included in the study. Somewhat paradoxically, however, the LSD test designated significant disparities among treatment means in only three of the six sampling periods. Nevertheless, a higher concentration in the burned portion of the cut-to-length subunit was distinguished against lower ones in the unthinned subunit irrespective of fire treatment in Period 1, against lower ones in all other treatment combinations in Period 5, and against lower concentrations in the unburned whole-tree and burned but unthinned combinations in Period 6. Regarding the sampling period effect on S discerned by ANOVA, perhaps its most obvious manifestation was the somewhat lower concentrations overall in Period 4.

Among micronutrients, significant influences on foliar Fe as revealed by ANOVA were those of sampling period ($p < 0.0001$) and the thinning × fire treatment ($p = 0.0374$), thinning treatment × sampling period ($p < 0.0001$), and fire treatment × sampling period ($p < 0.0001$) interactions (Table 2). With the exception of Period 4, the LSD test also differentiated numerous treatment combinations over the course of the study. In Period 1, significant differences were limited to that between a higher concentration in the unburned cut-to-length combination and a lower one in the unthinned but burned combination, but in Period 2, a higher concentration prevailed in the latter and a lower one in the former than in all remaining treatments. For Period 3 disparities, higher Fe in the unburned portions of the cut-to-length and whole-tree subunits contrasted with lower concentrations in the unthinned subunit irrespective of fire treatment, while in Period 5, higher Fe in the unburned whole-tree combination differed from the concentrations in every other combination except for that entailing the unthinned and unburned treatments. At the final sampling, however, the concentration in the burned portion of the unthinned subunit exceeded those in either portion of the whole-tree subunit. For the sampling period effect on Fe discerned by ANOVA, the average concentration across treatments was markedly elevated in Period 2 relative to that at the other samplings. Other than that of sampling period ($p = 0.0130$), significant influences on foliar Mn according to ANOVA consisted only of the thinning × fire treatment interaction ($p = 0.0358$), but the LSD test discerned significant treatment differences in every sampling period nonetheless. In Period 1, they consisted of a higher concentration in the burned portion of the whole-tree treatment than in all remaining treatment combinations except those in the cut-to-length subunit along with a higher one in the unburned portion of the latter than in the unburned whole-tree and burned but unthinned combinations. For Period 2, they were confined to a higher concentration in the burned portion of the whole-tree subunit than in that of the unthinned subunit, while in Period 3, the concentration in the unburned portion of the cut-to-length subunit exceeded those in the unburned portion of the whole-tree subunit and the burned and unburned portions of the unthinned subunit. Higher Mn in the burned portion of the whole-tree treatment than in that of the cut-to-length treatment plus those of the unthinned subunit irrespective of fire treatment along with a concentration in the unburned cut-to-length combination that exceeded those in both portions of the unthinned subunit constituted the significant disparities in Period 4. In Period 5, the concentration in the burned but unthinned combination exceeded that in its unburned counterpart plus those in the burned cut-to-length and unburned whole-tree combinations, while a higher one in the burned portion of the whole-tree subunit than in all remaining stand portions except that entailing the burned cut-to-length combination prevailed in Period 6. The sampling period effect on Mn disclosed by ANOVA was manifested in a somewhat lower average concentration in Period 3 and a higher one in Period 5 than at the remaining samplings. The sampling period effect on foliar Zn was significant ($p < 0.0001$) also, but the variation among periods was again subdued with somewhat lower average concentrations in Period 2 and to a lesser extent Period 3. Nevertheless, ANOVA discerned significant effects of fire treatment ($p = 0.0149$) and the thinning treatment × sampling period interaction ($p = 0.0051$) on Zn as well which were accompanied by significant differences among treatments at four of the six samplings according to the LSD test. Specifically, concentrations in the unburned portions of the cut-to-length and whole-tree subunits surpassed that in the burned portion of the unthinned treatment in Period 2 and again in Period 4. In Period 5, the concentration in the unburned whole-tree combination surpassed those in the burned portions of the cut-to-length and unthinned subunits while Zn in the unburned portions of the cut-to-length and unthinned treatments along with that in the burned whole-tree combination surpassed the concentration in the burned cut-to-length combination. For Period 6, concentrations in the unburned portion of the whole-tree treatment and in either portion of the unthinned subunit also exceeded the Zn in the burned cut-to-length combination.

Of the remaining micronutrients, foliar Cu was influenced by the fire treatment ($p = 0.0449$) and sampling period ($p < 0.0001$) plus the thinning × fire treatment interaction ($p = 0.0095$) according to ANOVA (Table 2), while significant treatment differences discerned by the LSD test were limited to one half of the samplings. Specifically, the concentration in the unburned portion of the cut-to-length treatment exceeded that in the burned portion of the whole-tree treatment in Period 2, the concentration in the former exceeded those of all other treatment combinations in Period 5, and the concentration in the former plus that in the burned whole-tree combination exceeded the Cu in the burned cut-to-length combination in Period 6. Regarding the sampling period effect noted above, Cu was lower overall in Period 1 and 4 than at the other samplings. Aside from a sampling period effect ($p < 0.0001$) on B, which was largely manifested in a higher average concentration in Period 1, the lone significant influence identified by ANOVA on this micronutrient was that of fire treatment ($p = 0.0208$). Nevertheless, the LSD test differentiated treatment differences in most of the samplings beginning in Period 1 when the concentration in the burned portion of the cut-to-length subunit exceeded those found in the unburned portions of the whole-tree and unthinned subunits and the concentration in the burned portion of the whole-tree treatment also exceeded that in its unburned counterpart. In Period 3, B in the burned portions of the whole-tree and unthinned subunits exceeded that in the unburned portion of the former, and the same disparity within the whole-tree treatment extended to Period 4. For Period 5, however, the concentration in the burned portion of the unthinned treatment was significantly higher than those in every other treatment combination except the burned whole-tree combination, and B in the latter was also higher than that in its unburned portion. Unlike the micronutrients, foliar Al was affected by thinning treatment ($p = 0.0024$), and ANOVA disclosed significant fire treatment ($p = 0.0014$) and sampling period ($p < 0.0001$) influences as well. As for the LSD test, it differentiated treatment combinations throughout the study, with those in Period 1 entailing higher concentrations in the burned portions of the cut-to-length and whole-tree subunits than those in the unburned portion of the latter and in the unthinned treatment in its entirety, and regarding Period 2, this same array of disparities was evident except that the burned unthinned combination did not differ significantly from any other treatment. For Period 3, concentrations were higher in the unburned portion of the cut-to-length and burned portion of the whole-tree subunits than in either portion of the unthinned treatment, while in Period 4, higher Al in the burned whole-tree combination differed significantly from that in all of the remainder except the unburned cut-to-length combination, and that in the latter exceeded the concentrations in the unburned whole-tree and unburned unthinned combinations as well. In Period 5, higher concentrations in the burned portions of the whole-tree and unthinned treatments differed from that in the unburned portion of the latter, while higher ones in the burned portions of the cut-to-length and whole-tree treatments did so regarding either portion of the unthinned treatment in Period 6. With regard to the sampling period effect on Al disclosed by ANOVA, foliar concentrations were higher overall in Period 1 and 2 and lower in Period 4 and 6.

Elemental concentrations in fully and partially elongated needles

For elemental concentrations confined to Period 5 but encompassing both fully and partially elongated needles, and thus those of the previous and current year, respectively, ANOVA revealed a needle year influence on N, P, and K (all $p < 0.0001$) along with a fire treatment effect ($p = 0.0479$) on the former (Table 3). The needle year influence on these three macronutrients was clearly reflected in the distinctions disclosed by the LSD test, which indicated that their concentrations were significantly higher in current than in previous year needles within every thinning and fire treatment combination. Providing further elucidation of the magnitude of these disparities is that the average concentration across treatments in the former exceeded that in the latter by 69% for N, 108% for P, and 58% for K. Also noteworthy for N and P was that the concentrations in current year needles significantly exceeded those in needles of the previous year in all comparisons across treatments, an outcome that also extended to K except for those between the unburned cut-to-length combination and the unburned whole-tree and burned but unthinned combinations. The other difference identified by the LSD test for N was confined to previous year needles and entailed a higher concentration in the burned cut-to-length combination than in the unburned whole-tree combination, a distinction reflective of the fire treatment effect noted above. The LSD test also disclosed as significant disparities within current year needles for P and K, specifically those between higher concentrations in the burned whole-tree stand portion and the burned and unburned portions of the unthinned subunit and a lower one in the unburned cut-to-length combination regarding the former, and a higher one in the unburned whole-tree treatment than in the unburned cut-to-length treatment for the latter. For Ca, significant influences disclosed by ANOVA were those of thinning treatment ($p = 0.0325$) and needle year ($p < 0.0001$). In the case of this macronutrient, however, concentrations were significantly higher in the needles of the previous year than the current year within every treatment concentration according to the LSD test and with that in the former exceeding the concentration in the latter by 117% on average. Furthermore, with the exceptions of those between the burned cut-to-length combination and the burned whole-tree and unburned and unthinned combinations, comparisons across treatments also revealed significant disparities between fully and partially elongated needles. The thinning influence on Ca was reflected in generally lower concentrations in the cut-to-length subunit, especially in previous year needles wherein the LSD test indicated that Ca in the burned portion of this subunit was exceeded by the concentration in the burned whole-tree combination and those in the unthinned subunit regardless of fire treatment. All effects on foliar Mg were non-significant according to ANOVA, although the LSD test disclosed a concentration in current year needles of the burned whole-tree combination that exceeded those of the same needles in every other treatment except the unburned whole-tree combination and also exceeded that in previous year needles of the burned but unthinned combination. Nevertheless, much more apparent were influences on S, as ANOVA identified those of the fire treatment ($p = 0.0013$) and needle year ($p = 0.0078$) along with the thinning treatment × needle year interaction ($p = 0.0015$) to be significant. The response of this element was unique among the macronutrients in that its concentration within one treatment combination, specifically the burned cut-to-length treatment, was significantly higher in previous year than in current year needles, while the reverse was true within two other treatments, namely the burned whole-tree and unburned unthinned combinations. Comparisons across treatment combinations reinforced this dichotomy, as the S concentration in previous year needles of the burned cut-to-length combination also exceeded those in current year needles of every other treatment except the burned whole-tree combination, while conversely, its concentration in current year needles of the latter exceeded those in previous year needles of every other treatment except the burned cut-to-length combination, and furthermore, S in current year needles of the unburned whole-tree and burned but unthinned combinations exceeded that in previous year foliage in the unburned and unthinned treatment. A final distinction revealed by the LSD test was perhaps the most apparent manifestation of the fire treatment influence on S, as its concentration in the burned portion of the cut-to-length subunit surpassed that in its unburned counterpart when values in the fully elongated needles of each were compared.

Thinning and fire treatment	**Needle year**	**Macronutrient concentration (%)**						**Micronutrient concentration (μg g^{-1})**					
Cut-to-length		N											
Burned	Previous	0.86b	0.10c	0.41d	0.24bc	0.11ab	0.11a	62cd	161abc	24d	2.6d	13cde	120abc
	Current	1.33a	0.21ab	0.72ab	0.12d	0.09b	0.07bcd	127a	83bc	29bcd	3.8cd	15bcde	84abcd
Unburned	Previous	0.71bc	0.10c	0.49d	0.30ab	0.11ab	0.06cd	53d	181abc	32abc	5.6a	13cde	92abcd
	Current	1.30a	0.18b	0.65bc	0.13d	0.10b	0.07bcd	107abc	89bc	36ab	5.4ab	14bcde	81abcd
Whole-tree													
Burned	Previous	0.84bc	0.10c	0.47d	0.35a	0.11ab	0.06cd	63bcd	238ab	33abc	4.0bcd	18ab	133a
	Current	1.43a	0.23a	0.79ab	0.17cd	0.13a	0.09ab	89abcd	124bc	32abc	4.6abc	16abcd	92abcd
Unburned	Previous	0.67c	0.11c	0.50cd	0.29ab	0.11ab	0.06cd	95abcd	145bc	38a	3.8cd	11e	97abcd
	Current	1.28a	0.21ab	0.83a	0.14d	0.11ab	0.08bc	53d	98bc	33abc	4.2abc	12de	47d
Unthinned													
Burned	Previous	0.83bc	0.11c	0.55cd	0.37a	0.10b	0.06cd	46d	323a	25cd	3.8cd	20a	127ab
	Current	1.29a	0.22a	0.79ab	0.14d	0.10b	0.08bc	112ab	81bc	28bcd	4.8abc	17abc	75abcd
Unburned	Previous	0.81bc	0.09c	0.43d	0.34a	0.11ab	0.05d	70bcd	167abc	33abc	3.8cd	13cde	68bcd

	Current	1.37a	0.22a	0.73ab	0.17cd	0.10b	0.08bc	67bcd	66c	30bcd	5.0abc	15bcde	61cd

Table 3: Foliar Concentrations of Nutrients and Al by Needle Year in Site Trees of a Pure, Uneven-Aged Jeffrey Pine Stand as Influenced by Mechanized Thinning and Prescribed Fire.[1]

[1]Within each element, means sharing a common letter do not differ significantly at α = 0.05 according to the LSD test; each mean was derived from concentrations in either fully or partially elongated needles of five trees (n = 5) of dominant or codominant crown class.

As for micronutrients, the effects of needle year ($p = 0.0083$) and the thinning treatment × needle year ($p = 0.0284$) and fire treatment × needle year ($p = 0.0170$) interactions were significant for Fe as disclosed by ANOVA (Table 3). According to the LSD test, significant disparities within treatments between previous and current year needles were confined to three treatments, specifically the burned and unburned cut-to-length combinations along with the burned but unthinned combination wherein the higher concentration was found in the partially elongated foliage in each case. Comparing across treatments, additional distinctions entailed higher Fe in current year needles of the burned cut-to-length combination than in previous year needles of every other treatment except the unburned whole-tree combination, a higher concentration in current year needles of the unburned cut-to-length combination than in the older ones of the burned but unthinned combination, and a higher concentration in current year needles of the burned but unthinned combination than in previous year needles of the burned and unburned cut-to-length combinations. Within current year foliage, the LSD test also identified as significant differences between higher Fe in the burned cut-to-length, unburned cut-to-length, and burned but unthinned combinations and a lower concentration in the unburned whole-tree combination as well as between a higher concentration in the former and lower one in the unburned and unthinned combination. The only influence on Mn revealed by ANOVA was needle year ($p = 0.0021$), but despite concentrations that were numerically greater in previous than in current year needles within every treatment combination, the LSD test identified as significant only the difference in the burned portion of the unthinned subunit. Nevertheless, across treatments, distinctions between fully and partially elongated foliage were prevalent, with the concentration in previous year needles of the burned but unthinned combination exceeding that in current year needles of every other treatment and a concentration in the older foliage of the burned whole-tree combination greater than that in younger needles of the unburned and unthinned combination as well. Independent of needle age considerations, the LSD test discerned a significant disparity between Mn concentrations in the burned but unthinned combination and the unburned whole-tree combination within previous year foliage in which the higher value prevailed in the former. Foliar Zn was among the few elements unaffected by needle year, as the sole significant effect on its concentration was that of fire treatment ($p = 0.0026$). This was manifested in generally higher values in the unburned than in the burned stand portions, while according to the LSD test, the concentration in previous year foliage of the unburned whole-tree treatment exceeded those in needles of both years in the burned cut-to-length and burned but unthinned treatments along with that in current year foliage of the unburned and unthinned combination. Additionally, Zn in the younger needles of the unburned cut-to-length treatment exceeded the concentrations in older foliage of burned portions of the cut-to-length and unthinned subunits, while its concentrations in previous year needles of unburned portions of the cut-to-length and unthinned subunits, in current year needles of the unburned whole-tree combination, and in both older and younger needles of the burned whole-tree combination exceeded that in previous year foliage of the burned cut-to-length treatment. For Cu, ANOVA again discerned a significant needle year effect ($p = 0.0268$) plus those of fire treatment ($p = 0.0264$) and the thinning × fire treatment interaction ($p = 0.0022$). Concerning the LSD test, distinctions between needle years all involved comparisons across treatments, with the concentration in the previous year foliage of the burned cut-to-length treatment exceeded by those in current year needles of every other treatment combination and the concentrations in older needles of the unburned whole-tree and two unthinned combinations exceeded by that in younger foliage of the unburned cut-to-length combination. Nevertheless, significant disparities within needle years were also prevalent, especially those involving the previous year needles of the unburned cut-to-length treatment which had the highest Cu concentration overall and one that exceeded those found in older foliage of every other treatment combination, while the concentration in the young needles of the former treatment combination also exceeded that in the young needles of its burned counterpart. Another elemental concentration unaffected by needle year was B, which like Zn was influenced by fire treatment only ($p=0.0004$). For this micronutrient, the LSD test disclosed as significantly dissimilar a B concentration that was higher in previous year needles of the burned but unthinned treatment than those in the cut-to-length subunit irrespective of fire treatment and foliar age as well as those in the unburned whole-tree and unburned unthinned stand portions irrespective of needle year; a concentration in previous year foliage of the burned whole-tree treatment that was higher than those of older needles in the entirety of the cut-to-length subunit and in the unburned portion of the unthinned subunit along with those in needles of either age in the unburned whole-tree stand portion; a concentration in current year needles of the burned but unthinned treatment that was also higher than those in the unburned whole-tree stand portion irrespective of foliar age; and higher B in current year needles of the burned whole-tree stand portion than that in the previous year foliage of the unburned counterpart. Regarding Al, ANOVA identified fire treatment ($p = 0.0233$) and needle year ($p = 0.0159$) as significant influences, but like Cu, manifestation of the latter in distinctions between needle years disclosed by the LSD test all involved comparisons across treatments. Specifically, concentrations in previous year foliage in the burned portions of the cut-to-length, whole-tree, and unthinned subunits exceeded that in current year needles of the unburned whole-tree combination, and those in older needles of the burned whole-tree and burned but unthinned combinations exceeded the concentration in younger needles of the unburned and unthinned combination as well. The remaining distinction was extant within previous year foliage where Al in the burned whole-tree treatment exceeded its concentration in the unburned and unthinned treatment.

General soil characteristics

Enumerated by treatment in the order of the cut-to-length burned, cut-to-length unburned, whole-tree burned, whole-tree unburned, unthinned burned, and unthinned unburned combinations, the textural analysis of the soil in the plots containing the site trees revealed that sand constituted 62, 56, 60, 57, 56, and 58% while silt was 22, 24, 22, 23, 24, and 22% and clay was 16, 20, 18, 20, 20, and 20% of the total mineral soil solids. Specific to these three variables, ANOVA disclosed that the sole significant effect was that of fire treatment ($p = 0.0097$) on clay, while the LSD test distinguished a higher sand content in the burned portion of the cut-to-length subunit from lower ones in its unburned counterpart and in the burned but unthinned stand portion along with higher clay in the unburned portions of the cut-to-length and whole-tree subunits plus the unthinned treatment in its entirety from a lower value in the burned portion of the cut-to-length treatment. Regardless, the soil throughout the study site was of the sandy loam textural class. Again enumerated in the order indicated above, soil organic matter content was 8.1, 10.6, 10.9, 8.4, 7.0, and 8.5% while the pH was 6.4, 6.2, 6.2, 6.3, 6.3, and 6.5. Of these two variables, ANOVA discerned only a thinning treatment effect ($p = 0.0406$) on the latter to be significant, and the LSD test indicated that the pH in the unburned and unthinned combination exceeded those in all other stand portions except the burned portion of the cut-to-length subunit.

Elemental concentrations in soil

Among macronutrients, thinning and fire treatment effects, along with that of their interaction, were nonsignificant concerning mineral soil concentrations of N, P1 and P2, K, and S according to ANOVA, and of these four concentrations, the LSD test discerned only a single significant difference pertaining to one element, specifically a higher K in the unburned portion of the whole-tree subunit than in the burned portion of the cut-to-length treatment (Table 4). As for the remaining macronutrients, however, ANOVA disclosed a thinning treatment ($p = 0.0229$) influence on Ca and one of fire treatment ($p = 0.0318$) on Mg, and the LSD test detected multiple significant dissimilarities concerning each. For Ca, these amounted to a higher concentration in the unburned portion of the unthinned subunit than in the burned portions of either the cut-to-length or whole-tree subunits along with a higher one in the burned portion of the former than in the burned cut-to-length combination. For Mg, higher concentrations in the unburned portions of all three thinning treatments and in the burned but unthinned combination contrasted against a lower one in the burned cut-to-length combination.

Thinning and fire treatment	Macronutrient concentration (%)							Micronutrient concentration (µg g-1)					
	N	P1	P2	K	Ca	Mg	S	Fe	Mn	Zn	Cu	B	Al (µg g^{-1})
Cut-to-length													
Burned													
Unburned	1103a	24a	42a	540ab	2108abc	377a	5a	39ab	31ab	1.5ab	0.5b	0.9a	10.0ab
Whole-tree													
Burned													
Unburned													
Unthinned													
Burned													
Unburned													

Table 4: Concentrations of Nutrients and Al in Mineral Soil near Site Trees in a Pure, Uneven-Aged Jeffrey Pine Stand as Influenced by Mechanized Thinning and Prescribed Fire.[1]

[1]Within each element, means sharing a common letter do not differ significantly at $\alpha = 0.05$ according to the LSD test; each mean was derived from concentrations in five composite samples ($n = 5$) consisting of 10 subsamples each.

Comparatively, influences on soil micronutrient concentrations were prevalent with B the only one for which ANOVA disclosed no significant effects, while Fe ($p = 0.0115$), Mn ($p = 0.0099$), Zn ($p = 0.0408$), and Cu ($p = 0.0043$) were all affected by fire treatment (Table 4). Regarding Fe, the LSD test discerned a significant disparity between higher Fe in the unburned portion of the whole-tree subunit and lower concentrations in the burned portions of this and the cut-to-length subunit, while for Mn, it distinguished a higher concentration in the former from lower ones in the burned portions of all three thinning treatments plus higher Mn in the unburned portions of the cut-to-length and unthinned subunits from a lower concentration in the burned cut-to-length combination. For Zn and Cu, concentrations in the unburned portion of the unthinned subunit exceeded those in burned stand portions irrespective of thinning treatment regarding the former and exceeded those in all other stand portions regarding the latter. Although ANOVA did not detect any significant effects on Al, the LSD test disclosed as a significant disparity that between a higher concentration in the burned portion of the whole-tree subunit and a lower one in the unburned and unthinned stand portion.

Foliar nutrition relationships

The mensuration subset of the first regression series produced 41 significant models (Table 5). Among them, foliar K in Period 2 and 3 and Mn in Period 2, 4, and 6 along with both of these plus Mg in partially elongated needles of Period 5, foliar S and Cu in Period 3, and Zn in Period 4 were all positively correlated with site tree height. Less prolific were models involving DBH, to which only foliar B in Period 1 was negatively related and K in Period 2, S in Period 3, and Mn and Zn in Period 4 were positively related. Nevertheless, live crown variables were well represented among significant models, with Fe and Zn in Period 1, the latter in Period 2, and Ca, Mn, and Zn in Period 3 along with the latter again in Period 4 each positively correlated while Fe in Period 2 and B in fully elongated needles of Period 5 were negatively correlated with live crown length. As for live crown percentage, positive correlations prevailed exclusively and featured Ca and Zn in Period 3 and Cu in Period 4 as dependent variables. Site tree age was the independent variable in several significant models where it was paired in positive relationships with foliar Cu in Period 3 and S in fully elongated needles from Period 5 while it was also paired with Zn and Cu in partially elongated needles of Period 5 entailing negative correlations. Only a single model proved to be significant involving site tree growth rate, to which foliar N in Period 4 was positively related. Of significant models incorporating stand density variables, basal area was the independent counterpart to Cu in Period 2 in a positive relationship but total tree count was the most prominent predictor of foliar values in this group by a substantial margin. Specifically, Al in Period 1 and P in Period 3 were positively correlated and Zn in Period 3 and 6 was negatively correlated with this independent variable. For live tree count, foliar Zn in Period 3 was its dependent counterpart in the lone significant relationship, a negative one. Total biomass was the independent variable in a modest number of significant models as well, with these featuring N in Period 1 in a negative correlation and Cu in Period 2 in a positive one. Although extensive, the mensuration subset was not notably forthcoming in its explanation of the variability in dependent variables reflecting foliar nutrition, as over 60% of them explained less than 20% of such variation while only two explained more than 30% and with the latter limited to models incorporating live crown measures exclusively.

Independent variables	Dependent variables	Correlation	Model F-test p-value	Model r^2
Mensuration subset:				
Height	Foliar K, Period 2, full elongation	Positive	0.049	0.1314
Height	Foliar Mn, Period 2, full elongation	Positive	0.0052	0.2466
Height	Foliar K, Period 3, full elongation	Positive	0.0073	0.2299
Height	Foliar S, Period 3, full elongation	Positive	0.014	0.1969
Height	Foliar Cu, Period 3, full elongation	Positive	0.0178	0.1846
Height	Foliar Mn, Period 4, full elongation	Positive	0.0033	0.2687
Height	Foliar Zn, Period 4, full elongation	Positive	0.0333	0.1519
Height	Foliar K, Period 5, partial elongation	Positive	0.0047	0.2523
Height	Foliar Mg, Period 5, partial elongation	Positive	0.0303	0.1569
Height	Foliar Mn, Period 5, partial elongation	Positive	0.03	0.1574
Height	Foliar Mn, Period 6, full elongation	Positive	0.0101	0.214
DBH	Foliar B, Period 1, full elongation	Negative	0.0246	0.1677
DBH	Foliar K, Period 2, full elongation	Positive	0.0198	0.1791
DBH	Foliar S, Period 3, full elongation	Positive	0.0484	0.132
DBH	Foliar Mn, Period 4, full elongation	Positive	0.0346	0.1498
DBH	Foliar Zn, Period 4, full elongation	Positive	0.0056	0.2436
Live crown length	Foliar Fe, Period 1, full elongation	Positive	0.0392	0.1432
Live crown length	Foliar Zn, Period 1, full elongation	Positive	0.0029	0.2753
Live crown length	Foliar Fe, Period 2, full elongation	Negative	0.0054	0.2456
Live crown length	Foliar Zn, Period 2, full elongation	Positive	0.0485	0.1319
Live crown length	Foliar Ca, Period 3, full elongation	Positive	0.0239	0.1693
Live crown length	Foliar Mn, Period 3, full elongation	Positive	0.0355	0.1484
Live crown length	Foliar Zn, Period 3, full elongation	Positive	0.0001	0.4146

Live crown length	Foliar Zn, Period 4, full elongation	Positive	0.0112	0.2084
Live crown length	Foliar B, Period 5, full elongation	Negative	0.0334	0.1517
Live crown percentage	Foliar Ca, Period 3, full elongation	Positive	0.0139	0.1973
Live crown percentage	Foliar Zn, Period 3, full elongation	Positive	0.0012	0.3154
Live crown percentage	Foliar Cu, Period 4, full elongation	Positive	0.0367	0.1467
Age	Foliar Cu, Period 3, full elongation	Positive	0.0065	0.2364
Age	Foliar S, Period 5, full elongation	Positive	0.0375	0.1455
Age	Foliar Zn, Period 5, partial elongation	Negative	0.0199	0.1789
Age	Foliar Cu, Period 5, partial elongation	Negative	0.0247	0.1676
Growth rate	Foliar N, Period 4, full elongation	Positive	0.0307	0.1562
Basal area	Foliar Cu, Period 2, full elongation	Positive	0.047	0.1336
Total tree count	Foliar Al, Period 1, full elongation	Positive	0.0203	0.1779
Total tree count	Foliar P, Period 3, full elongation	Positive	0.04	0.1421
Total tree count	Foliar Zn, Period 3, full elongation	Negative	0.0487	0.1317
Total tree count	Foliar Zn, Period 6, full elongation	Negative	0.0111	0.2089
Live tree count	Foliar Zn, Period 3, full elongation	Negative	0.0363	0.1473
Total biomass	Foliar N, Period 1, full elongation	Negative	0.0498	0.1305
Total biomass	Foliar Cu, Period 2, full elongation	Positive	0.006	0.2401
Fire injury subset:				
Bole char height	Foliar S, Period 2, full elongation	Negative	0.0086	0.2221
Bole char height	Foliar S, Period 4, full elongation	Negative	0.0439	0.1372
Percent bole char height	Foliar S, Period 2, full elongation	Negative	0.0092	0.2183
Percent bole char height	Foliar S, Period 4, full elongation	Negative	0.0288	0.1595
Percent bole char height	Foliar Ca, Period 4, full elongation	Negative	0.0316	0.1546
Bole char circumference	Foliar B, Period 5, full elongation	Positive	0.046	0.1347
Bole char circumference	Foliar Al, Period 6, full elongation	Positive	0.026	0.1649
Understory vegetation subset:				
Percent total ground cover	Foliar N, Period 1, full elongation	Negative	0.0114	0.2077
Percent total ground cover	Foliar K, Period 1, full elongation	Negative	0.0332	0.1519
Percent total ground cover	Foliar Ca, Period 1, full elongation	Positive	0.0036	0.2648
Percent total ground cover	Foliar K, Period 2, full elongation	Negative	0.0398	0.1424
Percent total ground cover	Foliar Ca, Period 2, full elongation	Positive	0.0042	0.2572
Percent total ground cover	Foliar Al, Period 3, full elongation	Negative	0.0499	0.1305
Percent total ground cover	Foliar Al, Period 4, full elongation	Negative	0.0134	0.1993
Percent total ground cover	Foliar Ca, Period 5, partial elongation	Positive	0.011	0.2092
Percent total ground cover	Foliar Zn, Period 6, full elongation	Positive	0.0159	0.1906

Forest floor fuels subset:				
1+10 hr fuels	Foliar Fe, Period 2, full elongation	Negative	0.0054	0.245
1+10 hr fuels	Foliar Cu, Period 2, full elongation	Positive	0.0494	0.131
1+10 hr fuels	Foliar Mn, Period 3, full elongation	Positive	0.0211	0.1759
1+10 hr fuels	Foliar S, Period 5, full elongation	Negative	0.0385	0.1441
1+10 hr fuels	Foliar Cu, Period 5, full elongation	Positive	0.004	0.2599
100 hr fuels	Foliar Mg, Period 1, full elongation	Positive	0.0013	0.3115
100 hr fuels	Foliar Ca, Period 4, full elongation	Positive	0.022	0.1736
100 hr fuels	Foliar Mg, Period 4, full elongation	Positive	0.017	0.1871
100 hr fuels	Foliar P, Period 5, partial elongation	Negative	0.0043	0.2562
100 hr fuels	Foliar K, Period 5, partial elongation	Negative	0.0253	0.1662
100 hr fuels	Foliar Mg, Period 5, partial elongation	Negative	0.042	0.1395
100 hr fuels	Foliar S, Period 5, partial elongation	Negative	0.0006	0.3512
100 hr fuels	Foliar Mg, Period 6, full elongation	Positive	0.0452	0.1357
1000 hr fuels	Foliar Al, Period 1, full elongation	Positive	0.0177	0.1848
1000 hr fuels	Foliar P, Period 2, full elongation	Positive	0.0198	0.1791
1000 hr fuels	Foliar Fe, Period 3, full elongation	Positive	0.0111	0.2088
1000 hr fuels	Foliar Al, Period 4, full elongation	Positive	0.0416	0.14
1000 hr fuels	Foliar S, Period 5, full elongation	Positive	0.0288	0.1595
1000 hr fuels	Foliar P, Period 5, partial elongation	Negative	0.0189	0.1815
1000 hr fuels	Foliar K, Period 5, partial elongation	Negative	0.0073	0.2302
1000 hr fuels	Foliar Zn, Period 5, partial elongation	Positive	0.0412	0.1405
Total fuels	Foliar Fe, Period 2, full elongation	Negative	0.0017	0.3016
Total fuels	Foliar Mn, Period 3, full elongation	Positive	0.0228	0.1717
Total fuels	Foliar Cu, Period 5, full elongation	Positive	0.0079	0.2264
Total fuels	Foliar P, Period 5, partial elongation	Negative	0.0337	0.1511
Soil influences subset:				
Soil K	Foliar K, Period 4, full elongation	Positive	0.0492	0.1311
Soil Al	Foliar Al, Period 1, full elongation	Positive	0.0044	0.2549
Soil Al	Foliar Al, Period 2, full elongation	Positive	0.0016	0.3037
Soil Al	Foliar Al, Period 4, full elongation	Positive	0.0058	0.2416

Table 5: Significant Simple Linear Regression Models Relating Foliar Nutrition of Site Trees in a Pure, Uneven-Aged Jeffrey Pine Stand as Influenced by Mechanized Thinning and Prescribed Fire to Mensurational, Fire Injury, Understory Vegetation, Fuels, and Soil Nutrition Variables.[1]

[1]All models incorporate 30 values each (n = 30) for the independent and dependent variables.

The fire injury subset was represented by seven significant models with the preponderance pertaining to bole char height measures (Table 5). Of these, both absolute and percent char height were independent variables to which foliar S in Period 2 and 4 were negatively related as was Ca at the latter sampling to percent height. For char circumference, B in fully elongated Period 5 foliage and the Al concentration in Period 6 were its dependent counterparts in positive relationships. The fire injury subset was especially weak in explaining

Citation: Walker RF, Fecko RM, Johnson DW, Miller WW (2016) Mechanized Thinning, Prescribed Fire, and Needle Age Influences on the Mineral Nutrition of Jeffrey Pine: Elemental Concentrations in Foliage and Soil. Forest Res 5: 172. doi:10.4172/2168-9776.1000172

extant variation in foliar nutrition with only two models that accounted for more than 20% of such variation.

The understory vegetation subset of the first series generated nine significant models featuring nearly equal representation of positive and negative correlations (Table 5). Concerning the latter, foliar N and K in Period 1, K again in Period 2, and Al in Period 3 and 4 were all negatively related to percent total cover while Ca in Period 1, 2, and 5 along with Zn in Period 6 were the dependent components in positive relationships. Overall, the understory vegetation subset was somewhat better than the mensuration and fire injury subsets in explaining the variation in the various dependent variables, as five of the models therein explained at least one-fifth of such variation.

The forest floor fuels subset of the first series yielded 25 significant models with each timelag category and the total all represented among their independent variables (Table 5). With 1+10 hr fuels serving as such, all except one model was specific to Period 2, when Fe was negatively related but Cu was positively related to this independent variable, and to the fully elongated needles of Period 5, in which Cu was again positively related while S was negatively so. As the exception, foliar Mn was positively correlated with the 1+10 hr categories in Period 3. More heavily represented were significant models incorporating 100 hr fuels, to which Mg in Period 1, Ca and Mg in Period 4, and the latter once again in Period 6 were positively related and to which P, K, Mg, and S in partially elongated needles of Period 5 were negatively so. Also heavily represented were models for which the 1000 hr category served as the independent variable, with which Al in Period 1 and 4, P in Period 2, Fe in Period 3, and S and Zn in fully and partially elongated needles, respectively, of Period 5 were positively correlated and with which P and K in partially elongated Period 5 needles were negatively so. Less numerous were models featuring total fuels as the independent component, with which Fe in Period 2 and P in partially elongated needles of Period 5 were paired in negative relationships while Mn in Period 3 and Cu in fully elongated Period 5 needles were the dependent counterparts in positive correlations. As for model strength in the fuels subset, nine of them explained at least one-fifth of the variation in the dependent variables of which three explained at least 30%.

The final subset of the first regression series, that encompassing soil nutrition influences on foliar nutrition, produced only four significant models, all entailing positive correlations (Table 5). These paired foliar K with soil K in Period 4 and foliar Al with soil Al in Period 1, 2, and 4. Although modest in number, this subset was perhaps the strongest overall of the five in the first regression series, as three of the models therein explained more than one-fifth of the variation in the dependent variables and with one of them accounting for 30%.

Soil nutrition relationships

The second regression series, which was concerned with the relationships between soil nutrition and both vegetation and site characteristics, generated 22 significant models (Table 6). For those focused on stand density in the independent component, soil organic matter was positively correlated with both the total and live tree counts, while models concerned with understory vegetation encompassed positive relationships between soil Ca and Cu and the percent total cover. With downed and dead fuels serving as the independent counterpart, dependent variables consisted of soil P1 and Mg paired with 100 hr fuels plus soil organic matter with 1000 hr fuels, all again featuring positive correlations. Relatively numerous were models involving soil texture, with Ca and Mg negatively related to percent sand, the latter positively correlated with percent silt, and soil Ca, Mg, Fe, Mn, Zn, and Cu positively related to percent clay. Soil pH served as the independent variable in significant models in which it was paired with organic matter, N, P1, B, and Al in negative relationships and with Ca in a positive one. Of the second regression series in its entirety, 55% of significant models explained more than 20% of the variation in their dependent variables while two-thirds of these explained more than 30% and nearly one half of them accounted for at least 40%, with models featuring stand density and soil texture variables as the independent components constituting the latter in its entirety.

Independent model variable r^2	**Dependent variable**	**Correlation**	**Model F test p-value**
Total tree count	Soil organic matter 0.4652	Positive	<0.0001
Live tree count	Soil organic matter 0.4515	Positive	<0.0001
Percent total ground cover	Soil Ca 0.1334	Positive	0.0466
Percent total ground cover	Soil Cu 0.2583	Positive	0.0041
100 hr fuels	Soil P1 0.1593	Positive	0.0289
100 hr fuels	Soil Mg 0.1550	Positive	0.0314
1000 hr fuels	Soil organic matter 0.1909	Positive	0.0158
Percent sand	Soil Ca 0.3391	Negative	0.0007
Percent sand	Soil Mg 0.4672	Negative	<0.0001
Percent silt	Soil Mg 0.1301	Positive	0.0498
Percent clay	Soil Ca 0.4030	Positive	0.0002
Percent clay	Soil Mg 0.4774	Positive	<0.0001

Citation: Walker RF, Fecko RM, Johnson DW, Miller WW (2016) Mechanized Thinning, Prescribed Fire, and Needle Age Influences on the Mineral Nutrition of Jeffrey Pine: Elemental Concentrations in Foliage and Soil. Forest Res 5: 172. doi:10.4172/2168-9776.1000172

Percent clay	Soil Fe 0.3863	Positive	0.0002
Percent clay	Soil Mn 0.1798	Positive	0.0195
Percent clay	Soil Zn 0.2327	Positive	0.0069
Percent clay	Soil Cu 0.3128	Positive	0.0013
Soil pH	Soil organic matter 0.1466	Negative	0.0367
Soil pH	Soil N 0.1304	Negative	0.0478
Soil pH	Soil P1 0.1308	Negative	0.0472
Soil pH	Soil Ca 0.1364	Positive	0.0446
Soil pH	Soil B 0.2088	Negative	0.0111
Soil pH	Soil Al 0.2510	Negative	0.0048

Table 6: Significant Simple Linear Regression Models Relating Soil Nutrition near Site Trees in a Pure, Uneven-Aged Jeffrey Pine Stand as Influenced by Mechanized Thinning and Prescribed Fire to Stand Density, Understory Vegetation, Fuels, Soil Texture, and Soil Acidity Variables.[1]
[1]All models incorporate 30 values each (n = 30) for the independent and dependent variables.

Discussion

The overarching interpretation to emerge from the extensive array of results presented from this study is that there was considerable variation among the various elemental concentrations investigated regarding their reactions in foliage to the thinning and fire treatments imposed therein. Among macronutrients, the N concentration was higher in thinned subunits of the stand at the initial foliar sampling, most apparently in the cut-to-length treatment, before transitioning to a relatively elevated concentration in the burned portion of either the cut-to-length or whole-tree subunits at every remaining sampling except the final one, with the initial response possibly reflecting diminished competition for this vital element given that foliar N in Period 1 was negatively correlated with total stand biomass which was lowest in the burned portion of the cut-to-length subunit and highest in the unburned and unthinned combination. As an aside, a negative correlation between foliar N at this sampling and ground cover abundance suggests that the N fixing capability of the two most prominent understory species on this site [47] was of little consequence to tree nutrition there. Nevertheless, with the implementation of the underburn following the initial sampling, the fire influence undoubtedly contributed to the ensuing N responses and possibly assumed the major role. In contrast, there was little evidence of either a thinning or fire treatment influence on foliar P while a somewhat sporadic thinning effect on K was manifested mostly in a higher concentration in the whole-tree subunit in Period 3 and to a lesser degree in Period 6. A fire influence on Ca, mostly amounting to higher concentrations in the unburned than burned portion of either the cut-to-length or unthinned subunits in Period 2 through 4, must be viewed skeptically because these disparities were also largely evident at the initial sampling and thus prior to the underburn, while a seemingly similar Mg response at the first sampling must be discounted for the same reason. A markedly higher foliar S in the burned cut-to-length treatment combination in Period 5 that persisted in somewhat subdued form through the final sampling can be more credibly attributed to the interaction of these two treatments despite a similar response in Period 1 because the disparity between this and the other treatment combinations was of such greater magnitude at the penultimate sampling. Whether it was happenstance or indicative of some degree of causation is unclear, but foliar S in Period 5 was positively correlated with 1000 hr fuels, and the burned portion of the cut-to-length subunit had among the highest loading in this timelag category [46]. In related studies and with the focus on foliar macronutrients, both Thibodeau et al. [48] and Lopez-Serrano et al. [49], working with balsam fir (*Abies balsamea* [L.] Mill.) and Aleppo pine (*Pinus halepensis* Mill.), respectively, noted that thinning increased N, P, and K but the latter study also disclosed that it depressed Ca and Mg, while Sala et al. [50] reported that neither thinning nor prescribed fire influenced N in ponderosa pine (Pinus ponderosa Dougl. Ex Laws.) as did Landsberg et al. [51] regarding underburning alone in this species, and Boyer & Miller [52] found that the latter treatment had no effect on foliar N, P, K, Ca, or Mg in longleaf pine (*Pinus palustris* Mill.). In a study concerned with multiple species, Minocha et al. [53] disclosed that N, P, K, Ca, and Mg were unaffected by underburning in Jeffrey pine, sugar pine (*Pinus lambertiana* Dougl.), and California white fir as well while thinning had no effect on any of these elements in sugar pine or white fir but increased foliar Mg in Jeffrey pine. When considered in total along with findings presented here, these studies indicate that foliar macronutrient responses to thinning and prescription fire exhibit a propensity to vary situationally according to species and site.

The pattern of wide variability in response to treatment prevailing here in macronutrients continued unabated in the micronutrients. Statistical distinctions among treatments were abundant for Fe and Mn, absent only at a single sampling for the former, with the unburned portion of the cut-to-length subunit exhibiting the highest overall Fe concentration within Period 1 and 3 and the burned but unthinned combination doing so in Period 2 and 6, while the highest Mn was associated with the burned portion of the whole-tree subunit in Period 1, 2, 4, and 6. Regarding Mn, it is perhaps notable that the pine component in this treatment combination had both the lowest growth [54] and highest mortality [46] encountered at the study site. Somewhat less abundant were significant treatment differences for Zn, but in Period 2, 4, 5, and 6 when such differences were detected, the unburned portion of either the cut-to-length or whole-tree subunits, or both, had the highest or near highest concentrations. Foliar Mn and Zn were heavily represented in significant regression models paired with mensurational measures as the independent variables which primarily indicated that their concentrations were higher in larger site trees with larger crowns, but the latter was also negatively related to total stem count in Period 6, and the unburned portion of the whole-tree subunit had the lowest count of the six treatment combinations. Foliar Cu differed among treatments at fewer samplings than any other micronutrient, but more often than not when differences occurred, the unburned cut-to-length combination produced the highest concentration. The most noteworthy aspect for B was that the highest concentration was routinely found in burned stand portions, specifically in Period 1, 3, 4, and 5, but over the course of the study each of the three thinning treatments were represented in this distinction. Nevertheless, at the penultimate sampling, B was found to increase with increasing bole char circumference. Comparatively little research has been conducted on the effects on micronutrients of the treatments included in the present study, but documented thus far is a finding by Boyer & Miller [52] that underburning did not influence foliar Fe, Mn, Zn, or Cu concentrations in longleaf pine while Minocha et al. [53] reported that its effect on Mn was negligible in Jeffrey pine, sugar pine, and white fir but that thinning increased this element in the former and decreased it in the latter. As for foliar Al, significant disparities abounded for this element in the present study as they did for micronutrients, with the highest concentrations prevailing in burned stand portions throughout the study and nearly exclusively in that within either the cut-to-length or whole-tree subunits which also frequently exhibited comparable values. Lending further clarity to this finding was a regression model that featured a positive relationship between Al concentration and bole char circumference in Period 6 plus others in Period 1 and 4 that positively correlated it with 1000 hr fuel loads, and not only did the burned cut-to-length treatment combination retain substantial post-fire fuels in this timelag category but it may be noteworthy that this combination exhibited mortality surpassed only by the burned whole-tree combination [46] and the second lowest growth in the pine component to that exhibited by the latter [54]. Analogous to their finding regarding Mn, Minocha et al. [53] detected no influence of underburning on Al in Jeffrey or sugar pine or white fir, but a wildfire in Sierra Nevada mixed conifer was found to raise foliar Al concentrations in the former over repeated samplings [55].

Independent of the various treatment influences on the foliar elemental concentrations investigated here, it was apparent for some that when the averages within sampling periods were compared across them, patterns emerged that may be related to the severity of the drought underway during the study which was initially extreme but became incrementally less so through the final year. Among the individual elements, B concentrations immediately decreased as the pronounced dearth of precipitation in the first year was somewhat alleviated in the second and they remained low through the third, while those of Al exhibited much the same response but at a more gradual pace. It has been previously documented that foliar nutrient concentrations can fluctuate with annual variation in precipitation [22], while results here extend this axiom to include a potentially harmful metallic element. Another form of variation in some other concentrations, again revealed when averages within sampling periods were compared across them, appeared to reflect the portion of the growing season during which the sampling was done. Specifically, foliar N was lower in mid-season than at early or late samplings, although in this case caution is warranted because only one of the six sampling periods was conducted at mid-season. Perhaps more reliably, average P and K concentrations were relatively low repeatedly in the early portion of the season and high in the late one but the opposite was apparent for Ca. Mechanistic interpretation of these patterns, particularly regarding growth implications, is complicated by the fact that because they are based on concentrations in fully elongated needles, early and mid-season samples were those of the previous year while the late sampling consisted of those of the current year.

Permitting a more definitive examination of the role of needle year in foliar nutrition was the mid-season sampling conducted in the final year of the study when both fully elongated previous year and partially elongated current year needles were included as separate entities. This revealed the influence of needle age to be pervasive in elemental concentrations although with a dichotomy in its influence. Among macronutrients, N, P, K, and to somewhat less degree S, were higher in the younger needles while Ca was higher in older ones, and among micronutrients, Fe and Cu were generally higher in the former with Mn so in the latter. Foliar Al was higher in older foliage as well. Collectively, these allocations indicate that at the peak of the growing season the nutrients most often limiting tree growth, N and P especially [22,23] but with K and S also essential, were partitioned to favor the foliar tissues undergoing active growth while concentrations of other elements, including Mn and Al that typically limit growth when excessively accumulated [18,22], were reduced either through retention in older tissues or through a dilution effect [56] caused by the rapid growth rate of young foliage. Thus, these findings largely conform to current knowledge concerning elemental mobility in trees, with N, P, K, and S among those recognized to be readily translocated while Ca is known to be highly immobile [57]. For the most part, the pattern revealed here concerning elemental partitioning between needles of differing maturity confirms that previously documented in Jeffrey pine [55], although S was not found to differ between needle ages in the prior study and the higher Fe concentration prevailed in older foliage previously. Nevertheless, regarding critical N in particular, its propensity toward translocation from older, senescing needles to younger, actively growing ones [22] and thus diminishing in concentration with advancing needle age [29] is borne out here in Jeffrey pine as it has been in lodgepole pine (*Pinus contorta* Dougl. ex Loud.), another western USA yellow pine species [58].

With treatment influences on mineral soil N, P1, P2, K, and S largely lacking, macronutrient responses therein were limited to a thinning effect on Ca, amounting to a higher concentration in the unthinned plots generally but most apparent in those not burned either, and a fire effect on Mg, manifested in higher concentrations in unburned than burned plots generally but most pronounced within the cut-to-length subunit. Among micronutrients, a fire effect was also imposed on Fe, Mn, Zn, and Cu, and again concentrations were generally higher in unburned stand portions with those in the whole-tree and unthinned subunits highest overall in the former two and latter two elements, respectively. It is apparent in these results that they present little support for the assertion that thinning elevates nutrient availability in proportion to the reduction in stocking [22]. Additionally, the under burning effects noted above, or for some nutrients the lack thereof, are equivocal in supporting the general assumption that temperate fire intensities increase N, P, and base cation availabilities while reducing those of metallic elements, at least temporarily [22,28,29], as compliance with this view here was confined to the latter. However, the lack of a requisite fire effect on soil pH and of any regression models demonstrating relationships between any metallic element and pH other than Al lends a degree of uncertainty concerning the finding of such an effect on the Fe, Mn, Zn, and Cu concentrations, and in fact, the regression analysis disclosed the only influence on all four of these elements to be soil texture, more specifically percent clay and with positive correlations prevailing throughout. Nevertheless, regarding Al, it is perhaps noteworthy that its concentration in the soil was an independent variable to which the foliar concentration was positively related at one half of the samplings in models that explained more of the variation in the dependent components than most of the others included in the study, although model strength therein was not exemplary overall. Attempts to tie foliar nutrition to that in the soil of western USA forest types have often been unsuccessful [58,59] although a previous study with Jeffrey pine and white fir on an eastern Sierran site [55] revealed some linkages which have been reinforced here for Al in the former species.

In summary, this study involved an examination of mineral nutrition in a pure, uneven-aged Jeffrey pine stand growing in the eastern Sierra Nevada upon which was imposed thinning and prescribed fire restoration treatments undergoing increasing usage regionally and elsewhere, with the former entailing both cut-to-length and whole-tree harvesting approaches and the latter consisting of a spring season underburn. Based on six samplings over multiple growing seasons of fully elongated needles from site trees selected for superior size and form, foliar N was higher in thinned subunits of the stand initially, most apparently in the cut-to-length treatment, before transitioning to a relatively elevated concentration in the burned portion of either the cut-to-length or whole-tree subunits throughout most of the remainder of the study, while higher foliar S in the burned cut-to-length treatment combination was evident in the last two sampling periods. Prominent among micronutrient responses was higher Mn in the burned whole-tree combination at a majority of the samplings, and equally often B was higher in burned stand portions but within the cut-to-length, whole-tree, or unthinned treatment depending on sampling period. Foliar Al was higher in burned stand portions even more often but nearly exclusively within either the cut-to-length or whole-tree treatments. As determined from a single mid growing season sampling at which both previous and current year needles were collected, N, P, K, S, Fe, and Cu were higher in the latter in large part while Ca, Mn, and Al were so in the former. Sampled near the midpoint of the study, mineral soil Ca was higher overall in the unthinned subunit while Mg, Fe, Mn, Zn, and Cu were generally higher in unburned stand portions. These findings promote understanding of the nutritional alterations that occur in Jeffrey pine and similar forests in response to common management practices and of the nutritional physiology of this species as it relates to the site it resides upon.

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References

1. Calkin DE, Gebert KM, Jones JG, Neilson RP (2005) Forest Service large fire area burned and suppression expenditure trends 1970-2002. Journal of Forestry 103: 179-183.
2. Stephens SL (2005) Forest fire causes and extent on United States Forest Service lands. International Journal of Wildland Fire 14: 213-222.
3. Westerling AL, Hidalgo HG, Cayan DR, Swetnam TW (2006) Warming and earlier spring increase western U.S. forest wildfire activity. Science 313: 940-943.
4. Miller JD, Safford HD, Crimmins M, Thode AE (2009) Quantitative evidence for increasing forest fire severity in the Sierra Nevada and southern Cascade Mountains, California and Nevada, USA. Ecosystems 12: 16-32.
5. Williams J (2013) Exploring the onset of high-impact mega-fires through a forest land management prism. Forest Ecology and Management 294: 4-10.
6. Agee JK (1993) Fire ecology of Pacific Northwest forests. Island Press, Washington DC.
7. Covington WW, Everett RL, Steele R, Irwin LL, Daer TA, et al. (1994) Historical and anticipated changes in forest ecosystems of the Inland West of the United States. Journal of Sustainable Forestry 2: 13-63.
8. Beesley D (1996) Reconstructing the landscape: An environmental history, 1820-1960. In Status of the Sierra Nevada: Vol. II, Assessments and scientific basis for management options pp: 3-24.
9. McKelvey KS, Skinner CN, Chang C, Erman DC, Husari SJ, et al. (1996) An overview of fire in the Sierra Nevada. In Status of the Sierra Nevada: Vol. II, Assessments and scientific basis for management options pp: 1033-1040.
10. Arno SF (2000) Fire in western forest ecosystems. In Wildland fire in ecosystems: Vol. 2, Effects of fire on flora, pp. 97-120 (Brown JK, Smith JK eds.). General Technical Report RMRS-GTR-42, USDA Forest Service, Ogden, UT, USA.
11. Lindstrom S, Rucks P, Wigand P (2000) A contextual overview of human land use and environmental conditions. In Lake Tahoe Watershed Assessment, Vol. I, pp. 23-127 (Murphy DD, Knopp CM eds.). General Technical Report PSW-GTR-175, USDA Forest Service, Berkeley, CA, USA.
12. Manley PN, Fites-Kaufman JA, Barbour MG, Schlesinger MD, Rizzo DM (2000) Biological integrity. In Lake Tahoe Watershed Assessment. pp 403-598.
13. Gruell, GE (2001) Fire in Sierra Nevada forests: A photographic interpretation of ecological change since 1849. Mountain Press, Missoula MT, USA.
14. Arno SF, Fiedler CE (2005) Mimicking nature's fire: Restoring fire-prone forests in the West. Island Press, Washington, DC.
15. Walker RF, Fecko RM, Frederick WB, Johnson DW, Miller WW (2007) Forest health impacts of bark beetles, dwarf mistletoe, and blister rust in a Lake Tahoe Basin mixed conifer stand. Western North American Naturalist 67: 562-571.
16. Edmonds RL, Agee JK, Gara RI (2011) Forest health and protection (2nd edn.). Waveland Press, Long Grove, IL, USA.
17. Van Mantgem PJ, Nesmith JCB, Keifer MB, Knapp EE, Flint A, et al. (2013) Climatic stress increases forest fire severity across the western United States. Ecology Letters 3: 1-6.
18. Kozlowski TT, Kramer PJ, Pallardy SG (1991) The physiological ecology of woody plants. Academic Press, New York, NY, USA.
19. Smith DM, Larson BC, Kelty MJ, Ashton PMS (1997) The practice of silviculture: Applied forest ecology (9th edn.). John Wiley and Sons, New York, NY, USA.
20. Nyland RD (2002) Silviculture: Concepts and applications (2nd edn.). McGraw-Hill, New York, NY, USA.
21. Tappeiner JC II, Maguire DA, Harrington TB (2007) Silviculture and ecology of western U.S. forests. Oregon State University Press, Corvallis, OR, USA.
22. Fisher RF, Binkley D (2000) Ecology and management of forest soils (3rd edn.). John Wiley and Sons, New York, NY, USA.
23. Binkley D (1986) Forest nutrition management. John Wiley and Sons, New York, NY, USA.
24. Husari S, Nichols HT, Sugihara NG, Stephens SL (2006) Fire and fuel management. In Fire in California's ecosystems 4: 444-466.

25. Vaillant NM, Fites-Kaufman J, Stephens SL (2009) Effectiveness of prescribed fire as a fuel treatment in Californian coniferous forests. International Journal of Wildland Fire 18: 165-175.
26. Fettig CJ, McKelvey SR, Cluck DR, Smith SL, Otrosina WJ (2010) Effects of prescribed fire and season of burn on direct and indirect levels of tree mortality in ponderosa and Jeffrey pine forests in California, USA. Forest Ecology and Management 260: 207-218.
27. Fule PZ, Crouse JE, Roccaforte J, Kalies EL (2012) Do thinning and/or burning treatments in western USA ponderosa or Jeffrey pine-dominated forests help restore natural fire behavior? Forest Ecology and Management 269: 68-81.
28. Wright HA, Bailey AW (1982) Fire ecology: United States and southern Canada. John Wiley and Sons, New York, NY, USA.
29. Pallardy SG (2008) Physiology of woody plants (3rdedtn). Academic Press, New York, NY, USA.
30. Dickinson MB, Johnson EA (2001) Fire effects on trees. In Forest fires: Behavior and ecological effects 6: 477-525.
31. Fites-Kaufman JA, Bradley AF, Merrill AG (2006) Fire and plant interactions. In Fire in California's ecosystems 7: 94-117
32. USDA Forest Service (1994) Soil survey of the Tahoe National Forest area, California. USDA Forest Service Pacific Southwest Region, San Francisco, CA, USA.
33. Fecko RM, Walker RF, Frederick WB, Johnson DW, Miller WW (2008) Influences of mechanized thinning and prescribed underburning on radial growth of Jeffrey pine. Journal of Sustainable Forestry 26: 19-60.
34. Walker RF, Fecko RM, Frederick WB, Murphy JD, Johnson DW, et al. (2006) Thinning and prescribed fire effects on forest floor fuels in the east side Sierra Nevada pine type. Journal of Sustainable Forestry 23: 99-115.
35. Curtis RO, Marshall DD (2000) Why quadratic mean diameter? Western Journal of Applied Forestry 15: 137-139.
36. Davis LC, Johnson KN, Bettinger PS, Howard TE (2001) Forest management (4th edn.). McGraw-Hill, New York, NY, USA.
37. Dunning D (1942) A site classification for the mixed conifer selection forests of the Sierra Nevada. Research Note 28, USDA Forest Service California Forest and Range Experiment Station, Berkeley, CA, USA.
38. Gholz HL, Grier CC, Campbell AG, Brown AT (1979) Equations for estimating biomass and leaf area of plants in the Pacific Northwest. Research Paper 41, Oregon State University Forest Research Laboratory, Corvallis, OR, USA.
39. Avery TE, Burkhart HE (2002) Forest measurements (5th edn.). McGraw-Hill, New York, NY, USA.
40. Helrich K (1990) Official methods of analysis of the Association of Official Analytical Chemists, Vol. 1 (15th edn.). Association of Official Analytical Chemists, Arlington, VA, USA.
41. Page AL, Miller RH, Keeney DR (1982) Methods of soil analysis: Part 2, Chemical and microbiological properties (2nd edn.). American Society of Agronomy, Madison, WI, USA.
42. Klute A (1986) Methods of soil analysis: Part 1, Physical and mineralogical methods (2nd edn.). American Society of Agronomy, Madison, WI, USA.
43. Walker RF, Swim SL, Johnson DW, Miller WW, Fecko RM (2014) Bark beetle demography in a Jeffrey pine stand as influenced by mechanized thinning and prescribed fire. Journal of Sustainable Forestry 33: 627-676.
44. Walker RF, Swim SL, Fecko RM, Johnson DW, Miller WW (2014) Influences of thinning and underburning restoration practices on red turpentine beetle demography in Jeffrey pine. Journal of Sustainable Forestry 33: 677-727.
45. Salverson WG, Walker RF, Fecko RM, Frederick WB, Johnson DW, et al. (2011) Influences of mechanized thinning and prescribed fire on understory vegetation in an uneven-aged Jeffrey pine stand. Journal of Sustainable Forestry 30: 823-849.
46. Swim SL, Walker RF, Johnson DW, Fecko RM, Miller WW (2014) Evaluation of mechanized thinning and prescribed fire effects on long-term fuels accumulations in uneven-aged Jeffrey pine. Journal of Sustainable Forestry 33: 827-859.
47. Bond G (1983) Taxonomy and distribution of non-legume nitrogen fixing systems. In Biological nitrogen fixation in forest ecosystems: Foundation and applications 32: 55-87.
48. Thibodeau L, Raymond P, Camire C, Munson A (2000) Impact of precommercial thinning in balsam fir stands on soil nitrogen dynamics, microbial biomass, decomposition, and foliar nutrition. Canadian Journal of Forest Research 30: 229-238.
49. Lopez-Serrano FR, de las Heras J, Gonzalez-Ochoa AI, Garcia-Morote FA (2005) Effects of silvicultural treatments and seasonal patterns on foliar nutrients in young post-fire Pinus halepensis forest stands. Forest Ecology and Management 210: 321-336.
50. Sala A, Peters GD, McIntyre LR, Harrington MG (2005) Physiological responses of ponderosa pine in western Montana to thinning, prescribed fire and burning season. Tree Physiology 25: 339-348.
51. Landsberg JD, Cochran PH, Finck MM, Martin RE (1984) Foliar nitrogen content and tree growth after prescribed fire in ponderosa pine. Research Note PNW-412, USDA Forest Service, Portland USA.
52. Boyer WD, Miller JH (1994) Effect of burning and brush treatments on nutrient and soil physical properties in young longleaf pine stands. Forest Ecology and Management 70: 311-318.
53. Minocha R, Turlapati SA, Long S, North M (2013) Fuel treatment effects on soil chemistry and foliar physiology of three coniferous species at the Teakettle Experimental Forest, California, USA. Trees 27: 1101-1113.
54. Swim SL, Walker RF, Johnson DW, Fecko RM, Miller WW (2013) Long-term growth responses of a Jeffrey pine stand to mechanized thinning and prescribed fire. Journal of Sustainable Forestry 32: 745-782.
55. Walker RF, Fecko RM, Johnson DW, Miller WW (2014) Mineral nutrition in Sierra Nevada mixed conifer: Wildfire effects, species distinctions, and temporal variation. Journal of Sustainable Forestry 33: 482-541.
56. Jarrell WM, Beverly RB (1981) The dilution effect in plant nutrition studies. Advances in Agronomy 34: 197-224.
57. Kramer PJ, Kozlowski TT (1979) Physiology of woody plants. Academic Press, New York, NY, USA.
58. Turner MG, Smithwick EAH, Tinker DB, Romme WH (2009) Variation in foliar nitrogen and aboveground net primary production in young postfire lodgepole pine. Canadian Journal of Forest Research 39: 1024-1035.
59. Imper DK, Zobel DB (1983) Soils and foliar nutrient analysis of Chamaecyparis lawsoniana and Thuja plicata in southwestern Oregon. Canadian Journal of Forest Research 13: 1219-1227.