**Forest Research**
**Open Access**

Walker et al., Forest Res 2016, 5:3
DOI: 10.4172/2168-9776.1000180

**Research Article** **Open Access**

# Elemental Ratios in Foliage and Soil of a Jeffrey Pine Stand Subjected to Thinning and Burning Restoration Practices

**Walker RF*, Fecko RM, Johnson DW and Miller WW**

*Department of Natural Resources and Environmental Science, University of Nevada, Reno, Nevada, USA*

## Abstract

Forest thinnings accomplished through cut-to-length and whole-tree harvesting followed by a prescribed underburn were assessed for their influences on mineral nutrition in eastern Sierran Jeffrey pine (*Pinus jeffreyi* Grev. & Balf.). As derived from foliar elemental concentrations determined at six samplings distributed over three growing seasons, molar Ca/Al, Mg/Al, K/Al, Ca/Mn, Mg/Mn, and K/Mn were generally higher in the unthinned treatment and lower in burned stand portions. Conducted under drought conditions, the driest phase of the study resulted in lower Ca/Al, Mg/Al, and K/Al and higher Ca/Mn and Ca/Zn when averaged across treatments. Foliar K/Mn, K/Zn, and K/Cu were generally lower in the early portion of the growing season compared to the late portion. At mid growing season, Mg/Al, K/Al, Mg/Mn, K/Mn, K/Fe, K/Zn, and K/Cu were higher in young needles while Ca/Al, Ca/Fe, Mg/Fe, Ca/Zn, Ca/Cu, and Mg/Cu were so in older ones. At mid study, soil Ca/Fe was higher in the unthinned treatment generally and especially in its unburned portion while K/Cu was higher overall in burned stand portions, most especially in the unthinned treatment. These findings provide insight into the interrelationships of base cations and metallic elements in forest nutrition as influenced by restoration practices.

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

## Introduction

The traditional rationale for density management has primarily concerned economic considerations, namely that thinning forest stands captures the monetary value of harvested trees before mortality associated with self-thinning renders them of little commercial value and that accelerated diameter growth of residual stems related to diminished competition for critical resources will enhance revenues at subsequent harvests when a price premium is realized from added volume concentrated in the remaining, and substantially enlarged, stand constituents [1,2]. Reductions in stocking levels have also often been viewed as a hedge against the spread of agents that can diminish forest health, particularly in conifer stands potentially subject to attacks by bark beetles where it is assumed that reduced competition will increase the vigor of residual stems, leaving them better able to resist attacks and more resilient when they occur [3,4]. With the profusion of wildfires and their heightened intensity in western USA conifer forests in recent years [5-9], the objective pursued in thinning operations, as often as not, has become to diminish the aerial fuels that permit the spread of crown fires [10]. Another management practice to undergo some transformation of purpose in the conifer forests of the American West is prescribed fire, particularly as used in the underburning of established stands, which heretofore was largely envisioned as a means to mimic historical fire regimes and therefore restore fire-dependent ecological processes [11,12]. In recent years, however, its use has increasingly revolved around surface and ground fuels reduction intended to interrupt the pathway between ground fires and tree crowns [13]. Nevertheless, regardless of the reasons for implementation, thinning and prescribed fire are both practices with consequences for long-term site productivity, perhaps most obviously concerning nutritional attributes. For the former, a generally held view is that nutrient supply per residual tree increases in approximate proportion to the reduction in stocking [14], but among factors unaccounted for is that the harvesting approaches followed in thinning operations differ widely in the amounts of slash retained onsite and the extent of forest floor and mineral soil disturbance, all of which have potentially substantial repercussions for nutrient budgets. As for prescribed fire, among the beliefs commonly held is that, reflecting the ash customarily generated, increases in the availability of base cations will raise soil pH with a resultant depression in the availability of metallic elements [11,12,14]. The latter assumption brings up an important aspect of forest nutrition regardless of research context that is frequently overlooked, specifically that nutritional adequacy is not only reflected in individual elemental availability and absorption but also in the availability and uptake of certain elements relative to those of others, although it is well recognized that balances among elemental concentrations are critical indicators of a healthy nutritional profile in both soils and plant tissues [14,15]. In particular, ratios of base cations to metallic elements, in recognition of their interrelationships and the phytotoxic potential of the latter, have become a recommended focus for heightened scrutiny in nutritional studies [16].

This study entailed an examination of nutrition embodied in foliage and soil in an eastern Sierra Nevada Jeffrey pine stand as influenced by mechanized thinning accomplished through two harvesting approaches that were each followed by prescribed underburning. Specifically determined were the ratios between selected elements in foliage over multiple post-treatment growing seasons accompanied by a mid-study assessment of the same in the soil, all of which was accompanied 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 assessing influences on the former.

---

***Corresponding author:** Walker RF, Department of Natural Resources and Environmental Science, University of Nevada, 1664 North Virginia Street, Reno, NV 89557, USA, Tel: 7757844039; E-mail: walker@cabnr.unr.edu

**Received** May 12, 2016; **Accepted** June 21, 2016; **Published** June 28, 2016

**Citation:** Walker RF, Fecko RM, Johnson DW, Miller WW (2016) Elemental Ratios in Foliage and Soil of a Jeffrey Pine Stand Subjected to Thinning and Burning Restoration Practices. Forest Res 5: 180. doi:10.4172/2168-9776.1000180

## Materials and Methods

### Study site and treatment installation

This study was conducted in a mid-elevation, uneven-aged, pure Jeffrey pine stand located on the Truckee Ranger District of the Tahoe National Forest. The site consists of 12.1 ha at an elevation of 1800 m with a generally northeast aspect (39º 25′ 45″ N, 120º 8′ 30″ W), while the slope varies from 3 to 12%. Precipitation is predominantly snowfall, and that for the year in which this study commenced was only 30 cm, a total that was 43% of the long-term annual average of 69 cm, 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. Soils are of the Kyburz-Trojan complex [17] and are well drained with a gravelly sandy loam surface layer and an andesitic substratum, while the site quality is $SI_{100}21$ (index height in meters) for Jeffrey pine [18].

Immediately following the conclusion of the growing season just prior to that during which the study commenced, division of the site into three subunits of equal size permitted the random assignment of each one of three thinning treatments, specifically a cut-to-length harvesting system, a whole-tree harvesting system, and an unthinned control, to a single subunit. The procedures embodied in these two widely disparate harvesting systems are revealed in Walker et al. [19], and they ultimately produce widely differing impacts on the forest floor, with the cut-to-length system retaining all slash onsite concentrated into elongated mats and entailing minimal disturbance of mineral soil, while the whole-tree system removes all slash from the site with substantial exposure and compacting of mineral soil in skid trails created by the extraction process. From the perspective of downed and dead fuels, the former augments preexisting loading while the latter renders it discontinuous. 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 approaches herein, a free thinning approach [20] was employed for release of select dominant and codominant crown class trees chosen for their superior growth form, while harvested stems were rarely <25.4 cm DBH (bole diameter 1.37 m aboveground) and those <20.3 cm DBH were felled only when they obstructed the harvesting operation.

At the onset of the growing season immediately following that during which this study commenced, one-half of each of the three subunits dedicated to the individual thinning treatments was randomly selected for under burning. The subunits were divided by 1.0 m wide hand lines with one of the two portions randomly designated to be burned and the other to remain unburned. For burned portions, 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 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 timelag categories. The average rate of spread was approximately 58 m $hr^{-1}$ and the average flame length was approximately 0.7 m.

### Vegetation and fuels measurements

Using 30 permanent 0.08 ha circular plots established immediately prior to the thinning operations which were evenly distributed over the six pending thinning and fire treatment combinations, mensurational attributes of the overstory were inventoried as necessary to determine from trees ≥ 10.2 cm DBH total height, DBH, live crown length, live crown percentage, species composition, and the density variables of total and live stem counts and basal area from which were also ascertained the post-thinning residual densities made possible by prior marking of the trees to be harvested. Mean DBH values by plot were calculated using the quadratic mean formula [21], while plot basal area was derived from quadratic mean DBH in combination with plot stem counts [22]. Also selected at this inventory was one unmarked dominant or codominant crown class site tree per plot for which total age and radial growth rate were measurements added to those noted above. Coring of the site trees (4.3 mm cores extracted 1.37 m above ground) permitted a determination of total age 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 produce their first countable ring at breast height [23], and growth rate was determined by counting the rings in the outermost 2.54 cm of each core. A second inventory was conducted at the conclusion of the final growing season included in the study that mimicked the first in all respects except that additional variables were quantified, specifically the bole char dimensionality values of height, percent height, and percent circumference, and the total overstory biomass. Specifically, bole char height was 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. 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. [24], and these quantities were then expressed by plot as the total of all components combined across species. As they reflect imposed treatment influences, measurements and derived values from the second inventory are of principal importance for the purposes of this study.

At the second overstory inventory, spatial quantification of the shrub and herbaceous understory vegetation occupying the site permitted the expression of the prevalence of such species on a percent ground cover basis and ultimately on a percent total cover basis, with the latter specifically pertinent to the study reported here. 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 detailed grid mapping to scale of the understory community. Also concurrent with the second inventory was one of downed and dead fuels, which entailed measurements by individual timelag category except for those designated as fine fuels, specifically the 1 hr and 10 hr categories, which were combined. These plus the coarse fuels, namely the 100 hr and 1000 hr categories, were combined to determine total loading as well. For 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 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 again. For 1000 hr fuels, however, lengths and the diameters at mid length were measured for use in the calculation of volume according to the Huber formula [25], and collection of 10 log sections from random locations outside the plots, measuring their dimensions, and then drying and weighing them provided a density constant for use in converting volume to dry weight by plot.

## Foliar and soil analyses

Foliar sample collection was distributed over six periods spanning three growing seasons. Period 1 sampling was conducted in late August of the first season, which was that following the implementation of the thinning treatments but before the underburn; the Period 2 and 3 samplings were conducted in late May and late August, respectively, of the second study season with the former occurring soon after underburn implementation; and those of Period 4, 5, and 6 were conducted in late May, early July, and late August, respectively, of the final season. Fully elongated needles were collected from each site tree at every sampling, thus constituting those of the previous year in Period 2, 4, and 5 but of the current year in Period 1, 3, and 6. For Period 5 only, additional samples consisting of partially elongated (approximately 60% of full), current year needles were collected as well, permitting an assessment of the influence of needle maturity on foliar nutrition. At every sampling, needle subsamples were severed from two small boughs selected from the middle one-third portion of the crowns of each site tree and combined into one composite sample per tree, with any needles exhibiting injury discarded. All samples were dried at 75°C for 24 hr, ground to pass a 20 mesh (850 µm opening) screen, and then analyzed for the base cations Ca, Mg, and K and the metallic elements Al, Mn, Fe, Zn, and Cu using inductively coupled plasma (ICP) spectroscopy after wet ashing with $HNO_3$ and $HClO_4$ [26]. From such concentrations 15 molar ratios were calculated entailing every combination of these base and metal constituents.

Near the midpoint of the study and coinciding with Period 3 foliar sampling, soil samples were collected near each site tree consisting of 10 subsamples extracted to a depth of 20 cm in mineral soil from random locations within the confines of each plot and then combined into one composite sample per plot. 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; Ca, Mg, and K by ICP spectroscopy after extraction with $NH_4C_2H_3O_2$; Al by ICP spectroscopy after extraction with KCl and Mn, Fe, Zn, and Cu by ICP spectroscopy after extraction with HCl [27,28]. Ultimately, the same array of molar ratios derived from the foliar tissues were calculated from these soil elemental concentrations.

## Statistical analyses

Because it was necessary to assign the thinning treatments to individual stand subunits with the underburn then assigned to one-half of each subunit, testing to confirm the independence of the plots within each thinning and fire treatment combination was warranted. Variables selected for this purpose 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 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 24 values of each for the entire stand. These were then incorporated into simple linear regression models by variable, with such models 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 the thinning and prescribed fire treatment effects plus that of sampling period along with all possible interactions. This analysis incorporated both the compound symmetry and first-order autoregressive covariance structures, with that ultimately relied upon being the one providing the lowest value for Akaike's Information Criterion (bias-corrected version, AICC). For foliar nutrition data pertaining to samples of partially elongated as well as those of fully elongated needles, three 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 the statistical analysis procedures imposed on the other data incorporated into this study, consult Walker et al. [29] for those concerned with initial stand level mensurational features derived from the first inventory, Walker et al. [30] for those specific to the final stand level mensuration and fire injury characteristics as quantified in the second inventory, Salverson et al. [31] for understory vegetation data, and Swim et al. [32] for those pertaining to downed and dead fuels.

Two series of simple linear regression models were computed to investigate linkages between variables selected as particularly pertinent to the nutrition of the subject stand, with the first series dedicated to foliar nutrition and the second to that of the soil. The extensive array of variables incorporated into the first series necessitated its division 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 molar ratios 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, specific molar ratios in soil were matched with those in foliage as the independent and dependent variables, respectively. 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 the molar ratios in the soil 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

### Overstory, understory, fuels, and site tree characteristics

At the initial inventory, the subject stand consisted of 97% Jeffrey pine and 3% California white fir (*Abies concolor* var. *lowiana* [Gord.] Lemm.) 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, and the pending residual basal area across all plots to be thinned averaged 16.7 $m^2$ $ha^{-1}$ dispersed over 304 stems $ha^{-1}$. At the second inventory, the Jeffrey pine component of the stand declined marginally to 96% with that of white fir increasing to 4%, and 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 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 this 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. As 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 only 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 combinations. Pretreatment and post-treatment characteristics of this stand are presented in greater detail in Walker et al. [29,30], respectively.

Enumerated in the order of the cut-to-length burned, cut-to-length unburned, whole-tree burned, whole-tree unburned, unthinned burned, and unthinned unburned treatment combinations, mean total post-treatment biomass was 71412, 84559, 76496, 79864, 86690, and 99353 kg $ha^{-1}$, respectively. The only significant effect discerned by ANOVA for this variable was that of the thinning × fire treatment interaction ($p=0.0498$), while 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.

As reported in greater detail by Salverson et al. [31] than here, the understory at the study site was dominated by shrubs, principally antelope bitterbrush (*Purshia tridentata* [Pursh] DC.) and mahala mat (*Ceanothus prostratus* Benth.). Across all treatments, total ground cover at the end of the study averaged 10.9%, with the highest found in the unburned portion of the unthinned subunit and the least in the burned portion of the whole-tree subunit. Exemplifying the paramount influence of the underburn irrespective of thinning treatment, total cover in unburned stand portions averaged 5.8 × that in burned portions.

Downed and dead fuel loading at the conclusion of the study was 47408 kg $ha^{-1}$ for the 1+10 hr timelag categories, 6252 kg $ha^{-1}$ for 100 hr fuels, 6200 kg $ha^{-1}$ for the 1000 hr category, and 59860 kg $ha^{-1}$ for total fuels when averaged across treatments. 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. For 100 hr and 1000 hr fuels, the burned portion of the unthinned treatment exhibited the least loading overall. Given its preeminence in each of the individual timelag 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. Additional details about the downed and dead fuel loading at this site are reported in Swim et al. [32].

Exclusively Jeffrey pine and serving as the subject specimens in the assessment of foliar nutrition, the site trees averaged 21.4 m in height, 43.5 cm DBH, 105 yrs of age, and 7.0 rings $cm^{-1}$ for their radial growth rate, and ANOVA identified all main and interaction effects on each of these variables to be non-significant. Regarding live crown, which averaged 12.8 m in length and 60% of total tree height across all treatment combinations, 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 ($p=0.0036$), while the LSD test disclosed 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, only site trees in burned stand portions exhibited bole char, 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 accompanied by significant disparities according to the LSD test between burned and unburned treatments within every thinning treatment. Within burned portions, however, this test also deemed significant differences between higher values in the cut-to-length treatment and lower ones in the unthinned treatment for char height and height percentage. Overall, site trees subjected to underburning exhibited a mean char height, height percentage, and circumference of 1.4 m, 7%, and 28%, respectively.

## Molar ratios in fully elongated needles

Concerning the molar ratios of metallic elements to base cations, significant influences on Ca/Al consisted of the thinning (p=0.0067) and fire (p=0.0099) treatments, sampling period (p<0.0001), and the thinning treatment × fire treatment × sampling period interaction (p=0.0370) according to ANOVA (Table 1). In Period 1, 2, and 5, the LSD test denoted as significant the differences between a higher Ca/Al in site trees of the unburned portion of the unthinned subunit and lower ones in every other treatment combination, and in Period 2, it also discerned such differences between the ratio in the unburned whole-tree combination and those associated with the burned portions of the cut-to-length and whole-tree subunits. Additionally, a higher Ca/Al in the unburned and unthinned combination contrasted against lower ones in the burned and unburned cut-to-length combinations and the burned whole-tree combination in Period 3 and 6 and against those in the burned and unburned cut-to-length combinations plus the burned whole-tree and burned unthinned combinations in Period 4. Furthermore, higher ratios in the unburned whole-tree and burned but unthinned combinations compared to that in the burned cut-to-length combination constituted other significant differences in Period 3, a higher one in the unburned whole-tree combination than in the burned portions of the cut-to-length and whole-tree treatments were the other significant distinctions in Period 4, and a higher one in the burned but unthinned combination than in the burned whole-tree combination was distinguishable in Period 6. As for the sampling period influence on Ca/Al discerned by ANOVA, this ratio was higher overall in Period 4, 5, and 6 than in Period 1, 2, and 3. For Mg/Al, ANOVA disclosed as significant effects of the thinning (p=0.0201) and fire (p=0.0127) treatments, sampling period (p<0.0001), and the fire treatment × sampling period (p=0.0137) and thinning treatment × fire treatment × sampling period (p=0.0235) interactions. Prevalent again were differences among treatments distinguished by the LSD test, and again

| Sampling period | Thinning treatment | Fire treatment | Ca/Al | Mg/Al | K/Al | Ca/Mn | Mg/Mn | K/Mn |
|---|---|---|---|---|---|---|---|---|
| 1[2] | Cut-to-length | Burned | 15.0b | 8.5bc | 25.4ab | 24.5bc | 14.6bc | 44.0ab |
| | | Unburned | 15.9b | 9.2bc | 23.9b | 22.1c | 12.9bc | 33.5b |
| | Whole-tree | Burned | 13.8b | 6.7c | 18.2b | 21.8c | 10.8c | 28.5b |
| | | Unburned | 19.7b | 13.4ab | 38.5a | 33.6abc | 22.4a | 63.0a |
| | Unthinned | Burned | 21.5b | 10.7abc | 30.9ab | 38.5ab | 19.2ab | 57.2a |
| | | Unburned | 33.6a | 15.7a | 26.5ab | 42.8a | 19.9ab | 34.4b |
| 2 | Cut-to-length | Burned | 12.7c | 9.2b | 18.5bc | 18.6c | 13.0ab | 27.2b |
| | | Unburned | 16.1bc | 9.5b | 21.9abc | 24.0bc | 14.4ab | 34.3ab |
| | Whole-tree | Burned | 13.1c | 7.5b | 15.8c | 18.9c | 11.0b | 23.0b |
| | | Unburned | 23.5b | 12.3ab | 27.5ab | 27.5ab | 13.9ab | 31.3ab |
| | Unthinned | Burned | 16.4bc | 10.6b | 23.3abc | 27.5ab | 18.1a | 42.3a |
| | | Unburned | 34.8a | 17.9a | 30.3a | 33.2a | 16.6a | 28.1b |
| 3 | Cut-to-length | Burned | 12.0c | 11.2bc | 31.4bc | 18.2c | 16.8bc | 46.3bc |
| | | Unburned | 14.2bc | 8.0c | 24.5c | 20.6c | 12.1c | 37.8c |
| | Whole-tree | Burned | 12.7bc | 8.2c | 29.9c | 24.1bc | 16.0bc | 57.2abc |
| | | Unburned | 17.3ab | 11.8bc | 49.7a | 29.9ab | 20.0ab | 84.6a |
| | Unthinned | Burned | 19.8ab | 14.4ab | 48.1ab | 27.9ab | 20.3ab | 68.4abc |
| | | Unburned | 26.7a | 17.4a | 48.5ab | 35.0a | 24.0a | 70.4ab |
| 4 | Cut-to-length | Burned | 17.2c | 14.8bc | 24.1cd | 21.5b | 18.8ab | 30.2ab |
| | | Unburned | 19.6bc | 10.4c | 21.4cd | 24.7ab | 13.2bc | 27.2b |
| | Whole-tree | Burned | 17.2c | 9.1c | 18.0d | 21.3b | 11.1c | 22.2b |
| | | Unburned | 32.0ab | 19.7b | 37.4ab | 25.0ab | 15.7abc | 32.5ab |
| | Unthinned | Burned | 23.2bc | 13.0bc | 29.4bc | 32.9a | 18.6ab | 41.3a |
| | | Unburned | 46.3a | 27.6a | 43.6a | 33.8a | 20.0a | 33.0ab |
| 5 | Cut-to-length | Burned | 14.7b | 11.5b | 26.9b | 21.1a | 16.8a | 38.2ab |
| | | Unburned | 22.5b | 14.3ab | 38.8ab | 23.2a | 14.6a | 40.4ab |
| | Whole-tree | Burned | 19.6b | 10.8b | 28.2b | 21.1a | 11.0a | 29.5b |
| | | Unburned | 20.7b | 12.8b | 35.6ab | 29.5a | 17.8a | 49.2a |
| | Unthinned | Burned | 26.8b | 15.1ab | 42.7a | 28.0a | 15.5a | 45.5ab |
| | | Unburned | 40.8a | 21.9a | 47.6a | 29.1a | 15.7a | 37.7ab |
| 6 | Cut-to-length | Burned | 17.2bc | 12.6b | 38.7b | 22.8ab | 15.9a | 49.0a |
| | | Unburned | 21.1bc | 17.3ab | 58.3ab | 21.8ab | 17.5a | 58.6a |
| | Whole-tree | Burned | 13.5c | 10.6b | 36.8b | 17.3b | 13.6a | 47.8a |
| | | Unburned | 31.7a | 22.0ab | 73.6a | 27.5a | 18.7a | 64.6a |
| | Unthinned | Burned | 27.7ab | 17.8ab | 57.9ab | 30.2a | 19.3a | 60.4a |
| | | Unburned | 33.2a | 25.1a | 66.3ab | 27.6a | 21.2a | 57.1a |

[1]Within each combination of ratio and sampling period, 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 fully elongated needles of five trees (n=5) of dominant or codominant crown class. [2]Prescribed underburn not yet implemented.

**Table 1:** Molar Ratios of the Base Cations Ca, Mg, and K to the Metallic Elements Al and Mn in the Foliage of Site Trees in a Pure, Uneven-Aged Jeffrey Pine Stand as Influenced by Mechanized Thinning and Prescribed Fire[1].

prominent was the high value prevailing in the unburned and unthinned treatment combination which significantly exceeded all others except the unburned whole-tree and burned but unthinned combinations in Period 1, all except the unburned whole-tree combination in Period 2, all except the burned but unthinned combination in Period 3, all others without exception in Period 4, all except the unburned cut-to-length and burned but unthinned combinations in Period 5, plus it surpassed those in the burned cut-to-length and burned whole-tree combinations in Period 6. Additional disparities consisted of a higher Mg/Al in the unburned than burned portion of the whole-tree subunit in Period 1, a higher one in the burned but unthinned combination than in the unburned cut-to-length and burned whole-tree combinations in Period 3, and a higher one in the unburned whole-tree combination than in its burned counterpart and that in the unburned portion of the cut-to-length treatment in Period 4. For the sampling period effect identified by ANOVA, Mg/Al was also higher overall in Period 4, 5, and 6 than in Period 1, 2, and 3. The K/Al ratio was influenced by the thinning ($p=0.0111$) and fire ($p=0.0037$) treatments along with sampling period ($p<0.0001$) according to ANOVA, but the latter effect was manifested differently than that regarding Ca/Al and Mg/Al with the average in Period 6 surpassing those at all prior samplings by a substantial margin. Furthermore, distinctions among treatment means revealed by the LSD test for this ratio indicated a somewhat reduced prominence for the unburned and unthinned combination, as the highest numerical value was extant there only in Period 2 when it surpassed those in the burned portions of the cut-to-length and whole-tree subunits, in Period 4 when is did so for all except the unburned whole-tree combination, and in Period 5 when it again exceeded those in the burned portions of the cut-to-length and whole-tree subunits. Otherwise, the highest value occurred in the unburned portion of the whole-tree treatment which exceeded that in its burned counterpart plus the one in the unburned cut-to-length combination in Period 1, surpassed that in its burned counterpart along with those in the cut-to-length subunit irrespective of fire treatment in Period 3, and was greater than that in its burned counterpart and in the burned portion of the cut-to-length subunit in Period 6. Other significant disparities for K/Al consisted of a higher value in the unburned than the burned portions of the whole-tree treatment in Period 2, higher ones in the unthinned subunit in its entirety than in the unburned cut-to-length and burned whole-tree combinations in Period 3, and a higher value in the unburned portion of the whole-tree treatment than in its burned counterpart and in the entirety of the cut-to-length treatment for Period 4.

Significant influences on Ca/Mn consisted of thinning treatment ($p=0.0077$), sampling period ($p<0.0001$), and the thinning treatment × sampling period interaction ($p=0.0070$) according to ANOVA (Table 1). Here also, treatment differences distinguished by the LSD test were prevalent, with an absence of them occurring only in Period 5. Otherwise, in Period 1 through 4, the highest numerical values occurred in the unburned and unthinned treatment combination and these differed significantly from the ratios in the cut-to-length subunit irrespective of fire treatment and that in the burned portion of the whole-tree subunit in Period 1 through 3 and from the values in the burned portions of the cut-to-length and whole-tree subunits in Period 4. Additional disparities in Period 1 consisted of higher Ca/Mn in the burned but unthinned combination than those in the unburned cut-to-length and burned whole-tree combinations, while in Period 2 and 3 they were comprised of higher ones in the burned but unthinned and the unburned whole-tree combinations than in the burned portions of the cut-to-length and whole-tree treatments regarding the former and in the entire cut-to-length subunit regarding the latter. Also, this ratio was significantly higher in the burned but unthinned combination than in the burned portions of the cut-to-length and whole-tree subunits in Period 4. For Period 6, values in the unthinned subunit irrespective of fire treatment and in the unburned whole-tree combination exceeded that in the burned counterpart of the latter. The sampling period influence on Ca/Mn revealed by ANOVA was manifested in a somewhat higher average in Period 1 than in the ensuing periods. ANOVA identified only the sampling period ($p<0.0001$) and the thinning treatment × sampling period interaction ($p=0.0181$) as significant influences on foliar Mg/Mn, with the lowest overall and highest overall averages across treatments occurring in Period 2 and 3, respectively. In Periods 1 through 4, the LSD test disclosed some significant differences among treatments for this ratio, consisting of a higher value in the unburned portion of the whole-tree subunit than in the remaining treatment combinations exclusive of the unthinned treatment in its entirety for Period 1 and higher ones in the latter than in the burned whole-tree combination for Period 1 and 2. Concerning Period 3, Mg/Mn in the unburned and unthinned combination exceeded the values in the remaining treatments exclusive of the unburned whole-tree and burned but unthinned combinations while those in the latter two combinations exceeded the value in the unburned cut-to-length combination, and in Period 4, the ratio in the unburned and unthinned combination exceeded those in the unburned cut-to-length and burned whole-tree combinations plus those in the burned portions of the cut-to-length and unthinned treatments surpassed that in the burned whole-tree combination. Effects disclosed by ANOVA as significant for K/Mn were sampling period ($p<0.0001$) and the thinning × fire treatment ($p=0.0188$) and thinning treatment × sampling period ($p=0.0463$) interactions, with the former influence apparent primarily in higher average values in Period 3 and 6 and lower ones in Period 2 and 4. According to the LSD test, significant disparities among treatments occurred in all except the last period, amounting to a higher K/Mn in the unburned portion of the whole-tree subunit and burned portion of the unthinned subunit than in either of their counterparts and in the unburned portion of the cut-to-length subunit at the initial sampling, while a higher value prevailed in the burned portion of the unthinned treatment than in its counterpart and the burned portions of the cut-to-length and whole-tree treatments in Period 2. For Period 3, a higher ratio prevailed in the unburned whole-tree combination than in either portion of the cut-to-length subunit along with a higher one in the unburned portion of the unthinned subunit than that in the unburned cut-to-length combination. Significant differences in Period 4 consisted of a higher value in the burned but unthinned combination than in the unburned cut-to-length and burned whole-tree combinations, while in Period 5 the only disparity was that between a higher K/Mn in the unburned than the burned portions of the whole-tree subunit.

The Ca/Fe ratio was affected by sampling period ($p<0.0001$) and the thinning × fire treatment ($p=0.0409$), thinning treatment × sampling period ($p=0.0223$), and fire treatment × sampling period ($p=0.0415$) interactions according to ANOVA (Table 2). Significant distinctions identified by the LSD test for this ratio consisted of a higher value in the unburned portion of the unthinned subunit than in all other treatment combinations except its burned counterpart in Period 1, while in Period 2, the value in the unburned portion of the cut-to-length subunit surpassed those in the other treatments without exception plus that in the unburned portion of the unthinned subunit surpassed the value in its burned portion. Thereafter, Ca/Fe was significantly higher in the unburned portion of the unthinned subunit than in the burned cut-to-length and unburned whole-tree combinations in Period 3 and

4 with an additional distinction between the former and its burned counterpart extant in the latter period. In Period 5, however, the ratio in the burned portion of the unthinned subunit exceeded those in all other treatments except the unburned cut-to-length combination, while in Period 6, that in the unburned whole-tree combination exceeded the value in the burned but unthinned combination. The sampling period influence detected by ANOVA for Ca/Fe was evident in substantially lower average values in Period 2 and 3 than at the remaining samplings. Influences on foliar Mg/Fe were limited to sampling period ($p<0.0001$) and the thinning treatment × sampling period interaction ($p=0.0309$) according to ANOVA, with the former effect largely manifested in a substantially lower average value in Period 2 and higher one in Period 6. Distinctions among treatments were discerned by the LSD test beginning in Period 2 when the ratio in the unburned cut-to-length combination exceeded those in every other treatment, and within the unthinned subunit, that in the unburned portion exceeded the value in its burned counterpart as well. In Period 3, Mg/Fe was greater in the unburned portion of the unthinned subunit than in the remaining stand portions except for its burned counterpart and the burned portion of the cut-to-length treatment, but the only significant disparity in Period 4 consisted of a higher value in the unburned than the burned portions of the unthinned subunit. For Period 5, Mg/Fe in the cut-to-length subunit irrespective of fire treatment and in the burned but unthinned combination exceeded that in the unburned whole-tree combination, while at the last sampling the ratio in the latter exceeded that in the burned but unthinned combination. Like Mg/Fe, significant influences on K/Fe were confined to sampling period ($p<0.0001$) and the thinning treatment × sampling period interaction ($p=0.0016$) according to ANOVA, and the former effect was again apparent primarily in an exceedingly low average for this ratio in Period 2 and a high one in Period 6. Furthermore, the LSD test again detected differences among treatments in all but one of the periods, but in this case the exception was Period 4. Nonetheless, it disclosed a higher K/Fe in the unburned whole-tree combination than in the unburned portion of the unthinned subunit in Period 1, a higher one in the unburned cut-to-length combination than in all other treatments in Period 2, and a higher one in the unburned and unthinned combination than in the former in Period 3. For Period 5, the LSD test distinguished a higher K/Fe in the burned portion of the unthinned subunit from lower values in every remaining stand portion except the unburned cut-to-length combination, and it did so regarding higher values in either portion of the whole-tree subunit and a lower one in the burned but unthinned combination for Period 6.

Significant influences discerned by ANOVA on Ca/Zn were limited to that of sampling period ($p<0.0001$), evident primarily in higher average values in Period 1 and 2 and lower ones in Period 3, 4, and 6, but the LSD test identified significant differences among treatments at four of the six samplings (Table 2. In Period 1, these consisted of a higher ratio in the unburned portion of the unthinned treatment than in all others except its burned counterpart and the burned whole-tree combination, and in Period 2 a higher value in the former differed from all except those in its counterpart and the unburned whole-tree combination. The next sampling at which significant disparities prevailed was Period 5 when Ca/Zn was higher in the burned portion of the unthinned treatment than in the unburned whole-tree combination, while in Period 6 that in the burned cut-to-length combination exceeded the values in the remaining stand portions without exception. ANOVA disclosed a sampling period effect ($p<0.0001$) plus that of the thinning treatment × sampling period interaction ($p=0.0131$) on Mg/Zn, with differences among treatments as detected by the LSD test confined to the last two samplings. Specifically, in Period 5 this ratio was significantly higher in the burned portion of the cut-to-length subunit than in any other treatment except the burned but unthinned combination, and that in the latter was higher than the value prevailing in the unburned whole-tree combination, while in Period 6 the value in the burned cut-to-length combination exceeded those in all stand portions other than its unburned counterpart. The sampling period influence on Mg/Zn revealed by ANOVA was largely evident in a somewhat higher average value in Period 2 and a lower one in Period 4. Influences on K/Zn detected by ANOVA were those of fire treatment ($p=0.0326$), sampling period ($p<0.0001$), and the thinning treatment × sampling period interaction ($p=0.0088$), with significant treatment disparities detected by the LSD test prevailing throughout the study. These consisted of a higher ratio in the burned portion of the cut-to-length subunit than in the unburned and unthinned combination in Period 1, a higher one in the burned but unthinned combination than in all other treatments except the former in Period 2, and a higher one in the unburned portion of the whole-tree subunit than in the unburned and unthinned combination in Period 3. For Period 4, K/Zn was higher in the burned portion of the unthinned subunit than in its unburned counterpart and in the burned cut-to-length combination, was higher in the former than in its counterpart and in the unburned whole-tree combination in Period 5, and was higher in the burned cut-to-length combination than in the unthinned subunit irrespective of fire treatment in Period 6. Regarding the sampling period influence discerned by ANOVA, K/Zn was somewhat higher on average in Period 3 and 6 and substantially lower overall in Period 4 than at the other samplings.

The sole significant effect on Ca/Cu was that of sampling period ($p<0.0001$), which was largely evident in a higher average in Period 1, and to a lesser extent in Period 4, along with lower ones in Period 2 and 3 (Table 2). The LSD test detected differences among treatments at only two samplings, namely Period 3 and 6, and with only one significant disparity in each. In the former, Ca/Cu was higher in the unburned and unthinned treatment combination than in the burned cut-to-length combination, while in the latter it was higher in the burned than in the unburned portions of the cut-to-length treatment. ANOVA revealed that sampling period ($p<0.0001$) plus the thinning × fire treatment interaction ($p=0.0461$) influenced Mg/Cu, with significant treatment dissimilarities detected by the LSD test at all but the first two samplings. Specifically, a higher value prevailed in the unburned portion of the unthinned subunit than in the whole-tree subunit irrespective of fire treatment in Period 3, that in the unburned portion of the whole-tree subunit exceeded the ratios in its burned counterpart and in the unburned and unthinned combination in Period 4, the ratio in the burned portion of the cut-to-length subunit exceeded that in its unburned counterpart in Period 5 and 6, and at the latter sampling, exceeded the value in the burned whole-tree combination as well. The sampling period effect disclosed by ANOVA was apparent primarily in a higher average Mg/Cu in Period 1, and to a lesser extent in Period 4, and a lower one in Period 2. The K/Cu ratio was also affected by sampling period ($p<0.0001$) and the thinning × fire treatment interaction ($p=0.0180$) according to ANOVA, and the LSD test again revealed treatment disparities at four of the six samplings, although in this case the exceptions were Period 1 and 3. For Period 2, K/Cu was higher in the burned whole-tree combination than in the unburned and unthinned combination, it was higher in the unburned whole-tree combination and in the burned but unthinned combination than in the latter in Period 4, it was higher in the burned but unthinned combination than in the unburned cut-to-length combination in Period 5, and was higher in the burned cut-to-length combination than in the burned portion of the whole-tree treatment in the final period. The sampling period influence noted above regarding this ratio was manifested in a higher average value in Period 1, and to a lesser extent in Period 6, and a lower one in Period 2.

## Molar ratios in fully and partially elongated needles

For the molar ratios encompassing both the fully and partially elongated needles of Period 5, and thus those of the previous and current year, respectively, nearly all were affected by needle year with most also influenced by other factors, and of the few for which foliar age was inconsequential, other factors surfaced as being significant regardless (Table 3). With Ca/Al, ANOVA identified the thinning (p=0.0009) and fire (p=0.0024) treatments along with needle year (p=0.0055) as influential, with the latter effect manifested in a significant disparity within only a single treatment combination according to the LSD test, specifically between a higher value in previous year needles and lower one in those of the current year within the burned but unthinned treatment. Comparison across treatments, however, revealed that the ratio in older needles of the unburned and unthinned treatment exceeded those in younger ones of every other combination, although it in fact surpassed those in all other treatments regardless of foliar age. Nevertheless, Ca/Al in previous year foliage of the burned but unthinned combination exceeded that in current year needles of the burned and unburned portions of the cut-to-length subunit along with the burned portion of the whole-tree subunit. Additionally, it was higher in younger foliage of the unburned and unthinned combination than in either older or younger needles of the burned cut-to-length stand portion as well as in the younger needles of the unburned cut-to-length, burned whole-tree, and burned but unthinned portions. Foliar Mg/Al was also affected by the thinning (p=0.0273) and fire (p=0.0029) treatments plus needle year (p=0.0174), and within treatments, the latter influence was again evident in only a single comparison according to the LSD test, specifically that entailing a higher value in current than in previous year needles of the unburned whole-tree combination. Regardless, comparisons across treatments yielded additional foliar age disparities in the case here as well, with the ratios in younger foliage of the unburned whole-tree and unburned unthinned combinations significantly exceeding those in the

| Sampling period | Thinning treatment | Fire treatment | Ca/Fe | Mg/Fe | K/Fe | Ca/Zn | Mg/Zn | K/Zn | Ca/Cu | Mg/Cu | K/Cu |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1[2] | Cut-to-length | Burned | 67.0b | 40.5a | 119.7ab | 182.9b | 111.4a | 327.4a | 2248.6a | 1254.3a | 3735.3a |
| | | Unburned | 68.9b | 39.5a | 104.1ab | 165.7b | 97.8a | 253.6ab | 2041.7a | 1224.7a | 3051.0a |
| | Whole-tree | Burned | 76.8b | 37.7a | 102.7ab | 195.7ab | 95.5a | 260.9ab | 2428.1a | 1158.5a | 3231.8a |
| | | Unburned | 67.0b | 48.1a | 146.6a | 166.7b | 103.4a | 298.1ab | 1947.8a | 1219.5a | 3150.6a |
| | Unthinned | Burned | 85.7ab | 42.7a | 122.7ab | 200.7ab | 103.4a | 297.5ab | 2169.5a | 1097.5a | 3047.8a |
| | | Unburned | 107.4a | 49.3a | 85.4b | 254.1a | 115.8a | 205.7b | 3225.1a | 1463.4a | 2614.7a |
| 2 | Cut-to-length | Burned | 22.0bc | 15.1bc | 31.4b | 188.7b | 130.8a | 276.1ab | 880.4a | 611.5a | 1276.5ab |
| | | Unburned | 64.8a | 32.9a | 73.8a | 168.9b | 96.3a | 231.1b | 902.6a | 496.5a | 1142.2ab |
| | Whole-tree | Burned | 27.3bc | 15.5bc | 33.3b | 190.7b | 108.0a | 232.8b | 1250.5a | 705.6a | 1514.1a |
| | | Unburned | 30.0bc | 14.2bc | 33.9b | 202.0ab | 97.3a | 221.6b | 1289.3a | 651.1a | 1438.6ab |
| | Unthinned | Burned | 13.3c | 9.2c | 23.7b | 211.1ab | 141.0a | 331.5a | 888.4a | 595.8a | 1344.7ab |
| | | Unburned | 37.8b | 18.7b | 31.6b | 288.0a | 139.0a | 238.6b | 1262.5a | 623.8a | 1051.0b |
| 3 | Cut-to-length | Burned | 33.2b | 31.3ab | 88.7ab | 113.8a | 103.1a | 283.1ab | 757.5b | 683.8ab | 1883.9a |
| | | Unburned | 43.9ab | 23.3b | 73.2b | 155.4a | 93.4a | 290.8ab | 1240.4ab | 714.3ab | 2208.7a |
| | Whole-tree | Burned | 44.0ab | 28.2b | 99.6ab | 138.8a | 92.7a | 329.2ab | 990.2ab | 653.3b | 2266.1a |
| | | Unburned | 36.9b | 25.1b | 102.8ab | 144.6a | 87.3a | 365.4a | 1070.8ab | 626.5b | 2586.1a |
| | Unthinned | Burned | 45.8ab | 33.3ab | 111.2ab | 136.2a | 97.1a | 318.7ab | 1134.9ab | 801.4ab | 2579.5a |
| | | Unburned | 62.9a | 41.5a | 119.3a | 134.2a | 90.2a | 268.1b | 1499.1a | 966.9a | 2712.1a |
| 4 | Cut-to-length | Burned | 63.8b | 45.8ab | 71.8a | 114.7a | 92.9a | 145.4b | 1404.1a | 1158.5ab | 1818.9ab |
| | | Unburned | 78.8ab | 41.5ab | 86.3a | 148.9a | 77.9a | 163.5ab | 2106.1a | 1115.0ab | 2214.1ab |
| | Whole-tree | Burned | 78.4ab | 39.9ab | 79.8a | 163.9a | 80.4a | 165.6ab | 1812.6a | 838.0b | 1796.2ab |
| | | Unburned | 57.5b | 35.9ab | 69.1a | 123.7a | 79.7a | 160.5ab | 2240.7a | 1437.2a | 2777.1a |
| | Unthinned | Burned | 57.7b | 34.3b | 78.0a | 156.4a | 89.2a | 202.7a | 1916.1a | 1184.6ab | 2771.7a |
| | | Unburned | 103.6a | 57.3a | 95.1a | 152.3a | 90.2a | 149.1b | 1467.4a | 853.6b | 1375.0b |
| 5 | Cut-to-length | Burned | 62.2b | 47.3a | 107.6b | 166.1ab | 129.2a | 280.9ab | 1499.1a | 1167.2a | 2587.6ab |
| | | Unburned | 80.0ab | 49.6a | 131.8ab | 155.9ab | 96.9bc | 270.5ab | 918.1a | 545.0b | 1457.8b |
| | Whole-tree | Burned | 78.0b | 40.5ab | 109.5b | 175.0ab | 90.3bc | 251.2ab | 1718.1a | 866.7ab | 2229.0ab |
| | | Unburned | 46.7b | 27.4b | 81.9b | 134.9b | 80.2c | 232.7b | 1322.3a | 831.9ab | 2319.7ab |
| | Unthinned | Burned | 116.7a | 52.9a | 173.9a | 264.2a | 114.8ab | 389.3a | 1966.8a | 807.5ab | 2819.3a |
| | | Unburned | 75.1b | 41.7ab | 99.6b | 167.7ab | 90.4bc | 220.3b | 1486.9a | 790.9ab | 1868.2ab |
| 6 | Cut-to-length | Burned | 82.2ab | 53.2ab | 162.1ab | 222.6a | 131.2a | 399.1a | 2217.0a | 1223.8a | 3494.4a |
| | | Unburned | 69.8ab | 57.1ab | 193.5ab | 130.2b | 101.8ab | 345.8ab | 936.9b | 718.6b | 2444.2ab |
| | Whole-tree | Burned | 84.1ab | 59.1ab | 206.8a | 142.4b | 95.3b | 337.2ab | 989.2ab | 681.2b | 2376.5b |
| | | Unburned | 95.9a | 65.3a | 227.9a | 144.3b | 95.3b | 334.4ab | 1414.6ab | 897.2ab | 3275.1ab |
| | Unthinned | Burned | 59.5b | 39.1b | 124.0b | 129.1b | 87.0b | 278.1b | 1133.3ab | 774.4ab | 2400.3ab |
| | | Unburned | 82.1ab | 60.5ab | 160.9ab | 126.6b | 95.6b | 261.6b | 1303.3ab | 939.0ab | 2694.3ab |

[1] Within each combination of ratio and sampling period, 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 fully elongated needles of five trees (n=5) of dominant or codominant crown class. [2] Prescribed underburn not yet implemented.

**Table 2:** Molar Ratios of the Base Cations Ca, Mg, and K to the Metallic Elements Fe, Zn, and Cu in the Foliage of Site Trees in a Pure, Uneven-Aged Jeffrey Pine Stand as Influenced by Mechanized Thinning and Prescribed Fire[1].

older foliage of all remaining treatment combinations, although such disparities extended to include the younger needles of the remaining combinations also. Other distinctions involving Mg/Al consisted of a higher value in previous year needles of the unburned and unthinned combination than in those of the same age in the burned portions of the cut-to-length and whole-tree treatments. The widest array of influences identified by ANOVA on any molar ratio was that pertaining to K/Al, which consisted of thinning (p=0.0032) and fire (p=0.0005) treatments, needle year (p<0.0001), and the fire treatment × needle year (p=0.0226) and thinning treatment × fire treatment × needle year (p=0.0312) interactions. Statistical distinctions by the LSD test were also numerous for this ratio beginning with those involving the highest values, which were found in current year foliage of the unburned portions of the whole-tree and unthinned subunits and which exceeded those of all other treatment combinations, previous and current year needles alike. Other disparities consisted of a higher ratio in current year foliage of the burned but unthinned combination than in that of the previous year regardless of treatment and higher ratios in younger needles of the burned and unburned cut-to-length and burned whole-tree combinations than those in older foliage of the burned portions of these two subunits.

Foliar Ca/Mn was somewhat anomalous among the molar ratios in that it was unaffected by needle year, but it was influenced by the thinning (p=0.0013) and fire (p=0.0125) treatments according to ANOVA (Table 3). Differences among treatments detected by the LSD test included a higher value in partially elongated needles of the unburned and unthinned combination than those in the cut-to-length subunit irrespective of fire treatment and needle age, the burned portions of the whole-tree and unthinned subunits irrespective of needle age, and the current year needles of the unburned whole-tree treatment. Additionally, Ca/Mn in older foliage of the unburned whole-tree and unthinned combinations exceeded the values in younger needles of the burned cut-to-length and burned and unburned whole-tree combinations, while that in older foliage of the burned but unthinned treatment exceeded the value in younger needles of the burned whole-tree combination. Foliar Mg/Mn was also somewhat anomalous among the molar ratios in that it was one of the few for which needle year (p<0.0001) was the sole significant influence discerned by ANOVA. As for the LSD test, it distinguished a higher value in younger needles of the unburned and unthinned treatment from lower ones in older foliage in the burned counterpart of this subunit and in the foliage of either age in all remaining stand portions. Furthermore, and perhaps more illuminating regarding the needle age effect, it deemed as significant differences between higher Mg/Mn in younger needles of the burned and unburned cut-to-length and burned but unthinned combinations and lower values in older foliage regardless of treatment, those between a higher ratio in younger needles of the unburned whole-tree combination and lower values in older ones of every other treatment combination, and those between a higher value in younger foliage of the burned whole-tree treatment and older needles in this and in the unburned cut-to-length combination. For K/Mn, ANOVA disclosed as significant the thinning treatment (p=0.0070), needle year (p<0.0001), and thinning treatment × needle year interaction (p=0.0153) effects. The influence of needle age on this ratio was readily apparent in the outcome of the LSD test, as higher values in current year foliage differed significantly from lower ones in older foliage in comparisons within and across all treatment combinations. Other distinctions regarding K/Mn were confined to current year needles only and consisted of a higher ratio in the unburned portion of the unthinned subunit than in all other combinations except its burned counterpart, and a higher ratio in the latter and in the burned cut-to-length combination than in the burned whole-tree treatment.

Significant influences on Ca/Fe were those of needle year (p<0.0001) and the fire treatment × needle year interaction (p=0.0189) according to ANOVA (Table 4). The LSD test supplied some supporting evidence for each of these in comparisons within treatment combinations, which indicated that this ratio was significantly higher in previous year than in current year needles in every treatment except the unburned whole-tree and unburned and unthinned combinations. Further evidence of higher values in older than in younger needles was provided by comparisons across treatments, as such disparities prevailed when the unburned cut-to-length, burned whole-tree, and unburned unthinned treatments were each contrasted against every other treatment combination with the exception of comparisons involving the current year foliage in the latter, and when the burned cut-to-length treatment was contrasted against the burned but unthinned combination. Nevertheless, the highest value for Ca/Fe was found in the older foliage of the burned but unthinned treatment, and it surpassed the ratios in all other treatments regardless of needle age. Another molar ratio that was somewhat anomalous in that it was unaffected by foliar age in and of itself was Mg/Fe, but ANOVA did identify the thinning treatment × needle year (p=0.0023) and fire treatment × needle year (p=0.0092) interactions as significant influences in this case which were manifested in some divergence regarding the disparities between old and young foliage as indicated by the LSD test. Specifically, the ratios were higher in previous than in current year needles for comparisons within and between the burned and unburned cut-to-length treatments and the burned but unthinned treatment and also for one between the unburned unthinned and burned cut-to-length treatments. Contrarily, however, Mg/Fe was higher in current than in previous year foliage in a comparison within the unburned whole-tree combination. Other significant dissimilarities for this ratio involved comparisons within needle ages, which for older foliage consisted of higher values in the burned and unburned cut-to-length and burned unthinned combinations than in the unburned whole-tree treatment, and for younger needles, higher ones in the latter and in the unburned and unthinned combination than those in the burned and unburned cut-to-length and burned but unthinned combinations. The K/Fe ratio was affected by needle year (p=0.0164) according to ANOVA along with the thinning treatment × needle year (p=0.0174) and fire treatment × needle year (p=0.0037) interactions, but here again mixed outcomes concerning foliar age influences were made apparent by the LSD test. Comparisons within and between the unburned whole-tree and unburned and unthinned combinations revealed higher K/Fe in younger than older needles, an outcome that extended to additional comparisons across treatments involving these two combinations juxtaposed against the burned and unburned cut-to-length and burned whole-tree treatments plus another between the latter and its unburned counterpart. In contrast, the reverse proved true in a comparison between the burned portions of the unthinned and cut-to-length subunits. The LSD test also disclosed several significant dissimilarities within needle ages, which amounted to a higher ratio in the burned but unthinned stand portion than in the unburned whole-tree combination for older foliage, and within younger needles, higher ones in the unburned portions of the whole-tree and unthinned subunits than in the cut-to-length subunit irrespective of fire treatment and the burned but unthinned combination.

The second of the molar ratios for which needle year (p<0.0001) constituted the sole significant influence as discerned by ANOVA was Ca/Zn, and the LSD test was largely corroborative in its assessment of foliar age effects as well with comparisons within treatment combinations revealing values that were significantly higher in fully than in partially elongated needles in all except the unburned whole-tree combination (Table 4). Furthermore, comparisons across treatments revealed a higher ratio in the former than the latter when the burned components of all three thinning treatments along with the unburned and unthinned combination were each contrasted against every other treatment combination, when the unburned cut-to-length treatment was contrasted against all except the unburned and unthinned combination, and when the unburned whole-tree treatment was contrasted against the cut-to-length treatment in its entirety. Significant distinctions within needle years were confined to older foliage and consisted of a higher Ca/Zn in the burned but unthinned treatment than in any other combination. Foliar Mg/Zn was the third and last of the molar ratios unaffected by needle year, but ANOVA did detect both fire treatment ($p=0.0057$) and thinning treatment × needle year interaction ($p=0.0107$) influences for this ratio. Its highest overall value was found in the burned portion of the cut-to-length subunit, more specifically in fully elongated foliage therein, and this was the only treatment combination within which a significant disparity prevailed between needle ages according to the LSD test, but this value also differed from those in the unburned portions of each thinning treatment regardless of foliar age as well as the ones in previous year needles of the burned whole-tree combination and current year needles in the burned but unthinned combination. Otherwise, Mg/Zn in older foliage of the burned but unthinned treatment exceeded the ratios in the unburned portions of the whole-tree and unthinned subunits irrespective of foliar age along with those in younger foliage from the burned and unburned cut-to-length treatments and older foliage from the burned whole-tree combination, while the ratio in younger foliage of the latter exceeded those found in younger needles of the unburned cut-to-length treatment and older ones of the unburned whole-tree treatment. For K/Zn, ANOVA again disclosed a fire treatment ($p=0.0198$) influence, but the needle year effect ($p<0.0001$) was significant also. Concerning the latter, comparisons within treatment combinations revealed higher values in current than in previous year foliage in all except the unburned cut-to-length and burned but unthinned treatments. Across treatments, values were higher in younger foliage of the burned but unthinned combination than in older needles of every other treatment, and for the burned cut-to-length, burned and unburned whole-tree, and unburned and unthinned combinations, the ratios in the younger needles of each exceeded those in older needles of the others along with that in previous year foliage of the unburned cut-to-length combination. Comparisons within needle years for K/Zn revealed a higher value in the burned but unthinned combination than in the remainder for older foliage and a higher one in the burned but unthinned treatment than in the unburned cut-to-length combination for young needles.

The third and last of the molar ratios for which needle year ($p<0.0001$) constituted the only significant influence detected by ANOVA was Ca/Cu, and for the most part, the treatment differences detected by the LSD test were confined to those reflective of its effect (Table 4). Specifically, comparisons both within and between treatment combinations involving the burned cut-to-length, burned whole-tree, and burned and unburned unthinned combinations revealed significantly higher values in previous than in current year needles, and such disparities were also evident when any of these four treatments were compared to the unburned cut-to-length and unburned whole-tree treatments. Furthermore, the ratio in older needles of the latter treatment exceeded those in younger ones of the unburned cut-to-length and burned but unthinned combinations as well. Within needle years, the lone significant dissimilarity discerned by the LSD test involved a higher Ca/Cu in older needles of the burned but unthinned combination and a lower one in older foliage of the unburned cut-to-length combination. For Mg/Cu, ANOVA disclosed as significant the effects of the fire treatment ($p=0.0357$) along with those of needle year ($p=0.0017$) and the thinning treatment × needle year interaction ($p=0.0288$). Pertinent to the needle age influence, the LSD test identified only a single significant disparity within treatment combinations, specifically that entailing a higher value in older than in younger foliage in the burned portion of the cut-to-length subunit, but across treatments, this value also exceeded those in young needles of every other treatment. Furthermore, the ratio in older foliage of the burned whole-tree combination exceeded those in young needles of the unburned cut-to-length plus burned and unburned unthinned combinations, while Mg/Cu in the older needles of the unburned whole-tree treatment exceeded that in younger ones of the unburned cut-to-length combination as well. Within older foliage, the LSD test identified the differences between a higher value in the burned cut-to-length treatment and lower ones in all others except the burned whole-tree combination as significant. Regarding K/Cu, ANOVA discerned the effects of fire treatment ($p=0.0472$) and needle year ($p=0.0217$) as significant, but the LSD test again detected only a single significant disparity between foliar ages within the various treatment combinations, that being one entailing a higher value in young needles of the unburned whole-tree combination and a lower one in older needles therein. Nevertheless, comparisons across treatments revealed that the former value also surpassed those in older foliage of the unburned cut-to-length, burned whole-tree, and unburned unthinned combinations, more of such disparities prevailed between the burned cut-to-length combination and its unburned counterpart along with the unburned and unthinned combination, and more still were extant between the burned portions of the whole-tree and unthinned subunits and the unburned cut-to-length treatment. Comparisons within needle years disclosed that K/Cu in the burned portions of the cut-to-length and unthinned subunits exceeded that in the unburned portion of the former for fully elongated foliage, while for that only partially elongated, the ratio in the unburned whole-tree combination exceeded those in unburned portions of the cut-to-length and unthinned subunits.

## General soil characteristics

In the order of the cut-to-length burned, cut-to-length unburned, whole-tree burned, whole-tree unburned, unthinned burned, and unthinned unburned treatment combinations, the textural analysis of the soil near 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. Of these three variables, ANOVA disclosed that the only significant effect was that of fire treatment ($p=0.0097$) on clay, but 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. Nevertheless, the soil was of the sandy loam textural class across the study site without exception. Also enumerated in order as 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 distinguished only a thinning treatment effect ($p=0.0406$) on the latter as 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.

## Molar ratios in soil

Of the three molar ratios involving Al, neither the thinning nor fire treatment effects, nor that of their interaction, constituted significant influences according to ANOVA, but in each case, the LSD test distinguished as significant some treatment differences (Table 5). Specifically, it denoted as statistically dissimilar a soil Ca/Al and Mg/Al in the unburned portion of the whole-tree subunit that exceeded the respective ratios in its burned counterpart and in the burned portion of the cut-to-length subunit, while K/Al adhered to this pattern also but for this ratio a significantly lower value in the unburned cut-to-length combination was evident as well. Somewhat similarly, molar ratios involving Mn were unaffected by treatment or treatment interaction according to ANOVA, while distinctions discerned by the LSD test were absent entirely for Ca/Mn and Mg/Mn, although a higher K/Mn in the burned portion of the cut-to-length treatment was disclosed as differing from lower values in its unburned counterpart and in the unburned and unthinned combination. For ratios involving Fe, ANOVA identified the thinning treatment (p=0.0425) as influencing Ca/Fe but disclosed all effects on Mg/Fe and K/Fe to be non-significant, while disparities deemed significant by the LSD test were also confined to the former and consisted of a higher Ca/Fe in the unburned portion of the unthinned treatment than in all others except its burned counterpart (Table 6). Absent entirely concerning any of the three molar ratios involving Zn were significant influences as derived from ANOVA and statistical dissimilarities as discerned by the LSD test. Of the ratios incorporating Cu, ANOVA detected a fire treatment influence (p=0.0080) on K/Cu but no significant effects regarding Ca/Cu or Mg/Cu, and distinctions among treatments according to the LSD test were also limited to the former amounting to a higher K/Cu in the burned portions of each of the three thinning treatments than in the unburned portion of the unthinned subunit.

## Foliar nutrition relationships

The mensuration subset of the first regression series produced 46 significant models (Table 7). Among them, foliar Ca/Cu in Period 2 and 4, K/Cu in Period 2 and 6, and Mg/Cu in Period 3 were positively related while Ca/Fe in the latter, Mg/Mn in Period 4 and 6, and K/Mn in Period 4 were negatively related to site tree height. Much less prolific were models involving DBH, to which only Ca/Zn in Period 1 was negatively related and K/Cu in Period 2 was positively so. Nevertheless, live crown variables were well represented among significant models, with Ca/Fe and Mg/Fe in Period 2 positively correlated while K/Mn and K/Zn in Period 1 and Mg/Zn in Period 3 were negatively correlated with live crown length. As for live crown percentage, models with positive correlations featured Mg/Fe in Period 2 and Ca/Fe in Period 3 as dependent variables while those with negative ones incorporated K/Zn in Period 1 and 3 plus that in partially elongated needles of Period 5 along with each of the three molar ratios involving Cu in Period 4 as dependent counterparts. Site tree age was the independent variable in several significant models where it was paired in positive relationships with K/Zn and K/Cu in the partially elongated needles from Period 5 and with Mg/Zn in Period 6, while it was also paired with Mg/Cu and K/Cu in Period 3 entailing negative correlations. Of significant models incorporating stand density variables, basal area was the independent counterpart to K/Fe in Period 4 in a positive relationship and to Ca/Mn in Period 6 in a negative one, but total tree count was the most prominent predictor of foliar values in this group by a substantial margin, and in most of these models negative relationships prevailed. Specifically, Ca/Al in Period 1, 3, and 6, K/Al in Period 1, Ca/Mn in Period 1, 2, 3, and 6, and K/Mn in Period 4 were negatively correlated while only Mg/Zn in Period 3 and K/Zn in Period 6 were positively correlated with this independent variable. For live tree count, foliar Mg/Zn in Period 3 plus Mg/Fe and K/Fe in Period 4 were its dependent counterparts in exclusively positive relationships. Total biomass was the independent variable in only a single significant model that featured Mg/Mn in Period 6 in a negative relationship. Although extensive, the mensuration subset was not notably forthcoming in its explanation of the variability in dependent variables reflecting foliar nutrition, as 80% of these models explained less than one-fifth of such variation.

The fire injury subset was represented by 13 significant models with a minority involving bole char height measures while the majority incorporated bole char circumference as the independent component (Table 7). Of the former, Mg/Cu in the fully elongated needles of Period 5 was positively related to both absolute and percent char height while K/Cu in fully elongated and K/Fe in partially elongated needles at this sampling were positively and negatively related, respectively, to the latter. For char circumference, K/Zn in partially elongated Period 5 foliage and in Period 6 were its dependent counterparts in positive relationships, while negative ones encompassed Ca/Al in Period 2 plus each of the three ratios involving Al in Period 5 and 6 serving as such but with the three at the penultimate sampling specific to partially elongated needles exclusively. The fire injury subset was especially weak in explaining extant variation in foliar nutrition, with all of the models therein accounting for less than 20% of such variation.

| Thinning treatment | Fire treatment | Needle year | Ca/Al | Mg/Al | K/Al | Ca/Mn | Mg/Mn | K/Mn |
|---|---|---|---|---|---|---|---|---|
| Cut-to-length | Burned | Previous | 14.7cd | 11.5c | 26.9d | 21.1bcd | 16.8de | 38.2d |
| | | Current | 10.6d | 13.7bc | 64.2bc | 19.8cd | 26.3b | 126.9b |
| | Unburned | Previous | 22.5bcd | 14.3bc | 38.8cd | 23.2bcd | 14.6e | 40.4d |
| | | Current | 12.7d | 13.8bc | 58.4bc | 23.7bcd | 27.1b | 113.2bc |
| Whole-tree | Burned | Previous | 19.6bcd | 10.8c | 28.2d | 21.1bcd | 11.0e | 29.5d |
| | | Current | 13.6d | 16.6bc | 63.6bc | 18.8d | 23.3bcd | 90.0c |
| | Unburned | Previous | 20.7bcd | 12.8bc | 35.6cd | 29.5ab | 17.8cde | 49.2d |
| | | Current | 21.4bcd | 28.1a | 124.8a | 19.7cd | 25.9bc | 118.8bc |
| Unthinned | Burned | Previous | 26.8bc | 15.1bc | 42.7cd | 28.0bc | 15.5de | 45.5d |
| | | Current | 13.0d | 14.6bc | 74.5b | 24.8bcd | 28.1b | 144.6ab |
| | Unburned | Previous | 40.8a | 21.9ab | 47.6cd | 29.1ab | 15.7de | 37.7d |
| | | Current | 29.3ab | 28.7a | 127.3a | 37.4a | 37.1a | 167.8a |

[1] Within each ratio, 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.

**Table 3:** Molar Ratios of the Base Cations Ca, Mg, and K to the Metallic Elements Al and Mn by Needle Year in the Foliage of Site Trees in a Pure, Uneven-Aged Jeffrey Pine Stand as Influenced by Mechanized Thinning and Prescribed Fire[1].

| Thinning treatment | Fire treatment | Needle year | Ca/Fe | Mg/Fe | K/Fe | Ca/Zn | Mg/Zn | K/Zn | Ca/Cu | Mg/Cu | K/Cu |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Cut-to-length | Burned | Previous | 62.2bc | 47.3a | 107.6bcd | 166.1b | 129.2a | 280.9cd | 1499.1ab | 1167.2a | 2587.6abc |
| | | Current | 16.5d | 21.5c | 97.2cd | 68.0e | 89.8cd | 423.6ab | 505.7cd | 675.1bcd | 3184.2ab |
| | Unburned | Previous | 80.0b | 49.6a | 131.8bcd | 155.9bc | 96.9bcd | 270.5cd | 918.1bcd | 545.0bcd | 1457.8d |
| | | Current | 28.0cd | 27.7bc | 119.3bcd | 67.3e | 77.7d | 332.1bc | 407.1d | 496.6d | 2082.3bcd |
| Whole-tree | Burned | Previous | 78.0b | 40.5abc | 109.5bcd | 175.0b | 90.3cd | 251.2cd | 1718.1ab | 866.7ab | 2229.0bcd |
| | | Current | 33.5cd | 40.9abc | 156.6abc | 86.0de | 107.8abc | 418.8ab | 592.8cd | 734.3bcd | 2843.7abc |
| | Unburned | Previous | 46.7bcd | 27.4bc | 81.9d | 134.9bcd | 80.2d | 232.7cd | 1322.3abc | 831.9bc | 2319.7bcd |
| | | Current | 38.6cd | 50.5a | 229.1a | 69.4de | 91.4cd | 415.1ab | 556.9cd | 723.0bcd | 3350.9a |
| Unthinned | Burned | Previous | 116.7a | 52.9a | 173.9ab | 264.2a | 114.8ab | 389.3ab | 1966.8a | 807.5bcd | 2819.3abc |
| | | Current | 19.0d | 22.2bc | 111.8bcd | 82.9de | 93.7bcd | 481.9a | 460.8d | 527.9cd | 2691.0abc |
| | Unburned | Previous | 75.1b | 41.7ab | 99.6bcd | 167.7b | 90.4cd | 220.3d | 1486.9ab | 790.9bcd | 1868.2cd |
| | | Current | 51.2bcd | 48.9a | 216.0a | 93.8cde | 90.6cd | 412.8ab | 555.3cd | 535.7cd | 2437.7bcd |

[1] Within each ratio, 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.

**Table 4:** Molar Ratios of the Base Cations Ca, Mg, and K to the Metallic Elements Fe, Zn, and Cu by Needle Year in the Foliage of Site Trees in a Pure, Uneven-Aged Jeffrey Pine Stand as Influenced by Mechanized Thinning and Prescribed Fire[1].

The understory vegetation subset of the first series generated 31 significant models, and all but one featured positive correlations (Table 7). Foliar Ca/Al, Mg/Al, and Ca/Mn in Period 1, 2, 3, 4 and in the partially elongated needles of Period 5, the former in fully elongated needles of Period 5 as well as in Period 6, K/Al in Period 4 and 5, Mg/Mn in Period 3, Ca/Fe in Period 1, 3, 4, and 5, Mg/Fe in Period 3 and 4, Ca/Zn in Period 1, 2, and 5, and Ca/Cu at the initial sampling were each positively correlated with understory cover. Conversely, the only negative relationship in this subset featured K/Zn in Period 1 as the dependent variable. Overall, the understory vegetation subset was better than the mensuration and fire injury subsets in explaining the variation in the dependent variables, as 45% of the models therein explained at least one-fifth of such variation and 13% of them explained approximately one-third of it.

The forest floor fuels subset of the first series yielded 29 significant models with each timelag category and the total all represented among their independent variables (Table 7). With 1+10-hr fuels serving as such, all models were specific to Period 2, when each of the molar ratios involving Fe was positively related to this independent variable, and to the fully elongated needles of Period 5, within which Mg/Cu was negatively so. More heavily represented were significant models incorporating 100-hr fuels, to which Mg/Cu in Period 1, Mg/Mn, Mg/Fe, and K/Fe in Period 2, and each of the ratios involving Al plus Mg/Mn and Mg/Fe in Period 6 were positively related. Even more heavily represented were models for which the 1000-hr category served as the independent variable, with which Ca/Al and Ca/Mn in Period 1, 2, and 3 plus Ca/Fe at the initial sampling, K/Al in Period 4, and Ca/Zn and K/Zn in partially elongated Period 5 needles were negatively correlated. Less numerous were models featuring total fuels as the independent component, with which K/Zn in partially elongated needles of Period 5 plus Mg/Cu and K/Cu in fully elongated ones of the same were paired in negative relationships while the three ratios involving Fe in Period 2 were the dependent counterparts in positive correlations. As for model strength in the fuels subset, 55% of them explained at least one-fifth of the variation in the dependent variables and nearly one-third of them explained at least 30% of such variation with the latter including two models that explained 55%, both featuring total fuels as the independent component.

The final subset of the first regression series, that encompassing soil nutrition influences on foliar nutrition, produced nine significant models with all entailing positive correlations (Table 7). These paired each of the ratios involving Al plus Mg/Mn in partially elongated Period 5 needles with their respective ratios in soil. Also, foliar Mg/Al in Period 1 was paired with soil Mg/Al, foliar K/Al in Period 1 and 3 was also paired with its soil counterpart, and foliar Mg/Mn in Period 2 and 4 was coupled with the same in soil as well. The soil influences subset was among the strongest overall of the five in the first regression series, as 55% of the models therein accounted for at least one-fifth of the variation in the dependent variables.

### Soil nutrition relationships

The second regression series, which was concerned with the relationships between soil nutrition and both vegetation and site characteristics, generated 41 significant models (Tables 8). For those focused on stand density in the independent component, Ca/Al, Mg/Al, and K/Al were each negatively related to stand basal area and the former and latter were negatively related to total tree count. Models concerned with understory vegetation encompassed a positive relationship between soil Ca/Fe and percent total cover plus negative ones between Mg/Cu and K/Cu and this independent variable. With downed and dead fuels serving as the independent counterpart, dependent variables consisted of K/Fe paired with the 1+10 hr timelag categories in a negative relationship along with soil Mg/Cu paired with 100-hr fuels and K/Cu coupled with 1000 hr fuels in positive ones. Numerous models involved soil texture, with Ca/Al, Mg/Al, Ca/Mn, Mg/Mn, Ca/Fe, Mg/Fe, Mg/Zn, and Mg/Cu all negatively related to percent sand while the three molar ratios pertaining to Mn plus Ca/Fe, Mg/Fe, Ca/Zn, Mg/Zn, Ca/Cu, and Mg/Cu were each positively correlated with percent silt. With both positive and negative relationships again represented, percent clay was also a prominent independent variable with which soil Ca/Al, Mg/Al, and Mg/Fe were positively correlated while K/Mn, K/Fe, K/Zn, and K/Cu were negatively so. Encompassing positive correlations exclusively, soil pH served as the independent variable in significant models in which it was paired with Ca/Al, each of the ratios involving Mn, Ca/Fe, and Ca/Zn. Of the second regression series in its entirety, 41% of significant models explained at least 20% of the variation in their dependent variables while over one-third of these explained at least 30%.

## Discussion

Considered in total, the array of base cation to metallic element molar ratios calculated here revealed that the mechanized thinning and prescribed fire treatment influences thereon were extensive but also as varied as they had been for the individual foliar concentrations from which they were derived [33]. For the ratios involving Al, the

| Thinning treatment | Fire treatment | Ca/Al | Mg/Al | K/Al | Ca/Mn | Mg/Mn | K/Mn |
|---|---|---|---|---|---|---|---|
| Cut-to-length | Burned | 155.7b | 32.1b | 47.7b | 132.2a | 26.1a | 44.8a |
| | Unburned | 310.9ab | 92.4ab | 58.7b | 95.9a | 28.0a | 27.9b |
| Whole-tree | Burned | 136.2b | 35.2b | 46.1b | 99.6a | 24.8a | 35.1ab |
| | Unburned | 536.3a | 165.1a | 148.3a | 97.8a | 27.0a | 29.6ab |
| Unthinned | Burned | 445.9ab | 109.1ab | 105.5ab | 148.1a | 36.8a | 36.2ab |
| | Unburned | 492.3ab | 115.6ab | 102.7ab | 130.5a | 30.6a | 27.9b |

[1] Within each ratio, 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 five composite samples (n=5) consisting of 10 subsamples each.

**Table 5:** Molar Ratios of the Base Cations Ca, Mg, and K to the Metallic Elements Al and Mn in the Mineral Soil near Site Trees in a Pure, Uneven-Aged Jeffrey Pine Stand as Influenced by Mechanized Thinning and Prescribed Fire[1].

| Thinning treatment | Fire treatment | Ca/Fe | Mg/Fe | K/Fe | Ca/Zn | Mg/Zn | K/Zn | Ca/Cu | Mg/Cu | K/Cu |
|---|---|---|---|---|---|---|---|---|---|---|
| Cut-to-length | Burned | 73.5b | 14.8a | 24.4a | 4148.0a | 794.2a | 1486.4a | 7406.0a | 1496.5a | 2435.6a |
| | Unburned | 75.6b | 22.2a | 20.4a | 2936.0a | 875.2a | 850.0a | 6962.0a | 2052.6a | 1899.4ab |
| Whole-tree | Burned | 78.2b | 19.7a | 27.1a | 3452.0a | 865.5a | 1216.6a | 6424.0a | 1606.6a | 2241.8a |
| | Unburned | 77.5b | 22.1a | 23.1a | 3412.0a | 916.3a | 1042.0a | 6161.0a | 1758.3a | 1829.6ab |
| Unthinned | Burned | 93.2ab | 23.8a | 23.3a | 3947.0a | 987.0a | 1023.4a | 8383.0a | 2146.2a | 2098.4a |
| | Unburned | 100.2a | 23.4a | 21.3a | 3087.0a | 685.6a | 698.5a | 5433.0a | 1249.5a | 1195.7b |

[1] Within each ratio, 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 five composite samples (n=5) consisting of 10 subsamples each.

**Table 6:** Molar Ratios of the Base Cations Ca, Mg, and K to the Metallic Elements Fe, Zn, and Cu in the Mineral Soil near Site Trees in a Pure, Uneven-Aged Jeffrey Pine Stand as Influenced by Mechanized Thinning and Prescribed Fire[1].

| Independent variable | Dependent variable | Correlation | Model p-value | $r^2$ |
|---|---|---|---|---|
| Mensuration subset: | | | | |
| Height | Foliar Ca/Cu, Period 2, full elongation | Positive | 0.0356 | 0.1483 |
| Height | Foliar K/Cu, Period 2, full elongation | Positive | 0.0051 | 0.2483 |
| Height | Foliar Ca/Fe, Period 3, full elongation | Negative | 0.0451 | 0.1358 |
| Height | Foliar Mg/Cu, Period 3, full elongation | Positive | 0.0123 | 0.2036 |
| Height | Foliar Mg/Mn, Period 4, full elongation | Negative | 0.006 | 0.24 |
| Height | Foliar K/Mn, Period 4, full elongation | Negative | 0.0465 | 0.1341 |
| Height | Foliar Ca/Cu, Period 4, full elongation | Positive | 0.0349 | 0.1493 |
| Height | Foliar Mg/Mn, Period 6, full elongation | Negative | 0.0481 | 0.1324 |
| Height | Foliar K/Cu, Period 6, full elongation | Positive | 0.0407 | 0.1412 |
| DBH | Foliar Ca/Zn, Period 1, full elongation | Negative | 0.0333 | 0.1518 |
| DBH | Foliar K/Cu, Period 2, full elongation | Positive | 0.0412 | 0.1406 |
| Live crown length | Foliar K/Mn, Period 1, full elongation | Negative | 0.047 | 0.1336 |
| Live crown length | Foliar K/Zn, Period 1, full elongation | Negative | 0.0456 | 0.1352 |
| Live crown length | Foliar Ca/Fe, Period 2, full elongation | Positive | 0.0341 | 0.1505 |
| Live crown length | Foliar Mg/Fe, Period 2, full elongation | Positive | 0.0213 | 0.1753 |
| Live crown length | Foliar Mg/Zn, Period 3, full elongation | Negative | 0.0251 | 0.1668 |
| Live crown percentage | Foliar K/Zn, Period 1, full elongation | Negative | 0.0415 | 0.1402 |
| Live crown percentage | Foliar Mg/Fe, Period 2, full elongation | Positive | 0.0395 | 0.1428 |
| Live crown percentage | Foliar Ca/Fe, Period 3, full elongation | Positive | 0.019 | 0.1812 |
| Live crown percentage | Foliar K/Zn, Period 3, full elongation | Negative | 0.0083 | 0.2236 |
| Live crown percentage | Foliar Ca/Cu, Period 4, full elongation | Negative | 0.0191 | 0.1809 |
| Live crown percentage | Foliar Mg/Cu, Period 4, full elongation | Negative | 0.0453 | 0.1355 |
| Live crown percentage | Foliar K/Cu, Period 4, full elongation | Negative | 0.0328 | 0.1526 |
| Live crown percentage | Foliar K/Zn, Period 5, partial elongation | Negative | 0.0208 | 0.1765 |
| Age | Foliar Mg/Cu, Period 3, full elongation | Negative | 0.0384 | 0.1443 |
| Age | Foliar K/Cu, Period 3, full elongation | Negative | 0.0086 | 0.2216 |
| Age | Foliar K/Zn, Period 5, partial elongation | Positive | 0.004 | 0.2605 |
| Age | Foliar K/Cu, Period 5, partial elongation | Positive | 0.0041 | 0.2584 |
| Age | Foliar Mg/Zn, Period 6, full elongation | Positive | 0.0127 | 0.2019 |
| Basal area | Foliar K/Fe, Period 4, full elongation | Positive | 0.0208 | 0.1765 |
| Basal area | Foliar Ca/Mn, Period 6, full elongation | Negative | 0.0296 | 0.158 |
| Total tree count | Foliar Ca/Al, Period 1, full elongation | Negative | 0.0484 | 0.132 |
| Total tree count | Foliar K/Al, Period 1, full elongation | Negative | 0.0467 | 0.134 |

| | | | | |
|---|---|---|---|---|
| Total tree count | Foliar Ca/Mn, Period 1, full elongation | Negative | 0.0186 | 0.1823 |
| Total tree count | Foliar Ca/Mn, Period 2, full elongation | Negative | 0.0436 | 0.1376 |
| Total tree count | Foliar Ca/Al, Period 3, full elongation | Negative | 0.0296 | 0.1581 |
| Total tree count | Foliar Ca/Mn, Period 3, full elongation | Negative | 0.0112 | 0.2085 |
| Total tree count | Foliar Mg/Zn, Period 3, full elongation | Positive | 0.0251 | 0.1667 |
| Total tree count | Foliar K/Mn, Period 4, full elongation | Negative | 0.0291 | 0.1589 |
| Total tree count | Foliar Ca/Al, Period 6, full elongation | Negative | 0.0482 | 0.1323 |
| Total tree count | Foliar Ca/Mn, Period 6, full elongation | Negative | 0.0315 | 0.1548 |
| Total tree count | Foliar K/Zn, Period 6, full elongation | Positive | 0.0181 | 0.1838 |
| Live tree count | Foliar Mg/Zn, Period 3, full elongation | Positive | 0.0348 | 0.1495 |
| Live tree count | Foliar Mg/Fe, Period 4, full elongation | Positive | 0.049 | 0.1314 |
| Live tree count | Foliar K/Fe, Period 4, full elongation | Positive | 0.0385 | 0.1442 |
| Total biomass | Foliar Mg/Mn, Period 6, full elongation | Negative | 0.0471 | 0.1323 |
| Fire injury subset: | | | | |
| Bole char height | Foliar Mg/Cu, Period 5, full elongation | Positive | 0.0377 | 0.1453 |
| Percent bole char height | Foliar Mg/Cu, Period 5, full elongation | Positive | 0.0264 | 0.1641 |
| Percent bole char height | Foliar K/Cu, Period 5, full elongation | Positive | 0.0434 | 0.1378 |
| Percent bole char height | Foliar K/Fe, Period 5, partial elongation | Negative | 0.042 | 0.1396 |
| Bole char circumference | Foliar Ca/Al, Period 2, full elongation | Negative | 0.0467 | 0.1339 |
| Bole char circumference | Foliar Ca/Al, Period 5, partial elongation | Negative | 0.0357 | 0.1481 |
| Bole char circumference | Foliar Mg/Al, Period 5, partial elongation | Negative | 0.0372 | 0.146 |
| Bole char circumference | Foliar K/Al, Period 5, partial elongation | Negative | 0.0295 | 0.1583 |
| Bole char circumference | Foliar K/Zn, Period 5, partial elongation | Positive | 0.0366 | 0.1468 |
| Bole char circumference | Foliar Ca/Al, Period 6, full elongation | Negative | 0.0283 | 0.1605 |
| Bole char circumference | Foliar Mg/Al, Period 6, full elongation | Negative | 0.0413 | 0.1405 |
| Bole char circumference | Foliar K/Al, Period 6, full elongation | Negative | 0.0495 | 0.1319 |
| Bole char circumference | Foliar K/Zn, Period 6, full elongation | Positive | 0.0484 | 0.1321 |
| Understory vegetation subset: | | | | |
| Percent total ground cover | Foliar Ca/Al, Period 1, full elongation | Positive | 0.0008 | 0.3346 |
| Percent total ground cover | Foliar Mg/Al, Period 1, full elongation | Positive | 0.0131 | 0.2006 |
| Percent total ground cover | Foliar Ca/Mn, Period 1, full elongation | Positive | 0.0118 | 0.206 |
| Percent total ground cover | Foliar Ca/Fe, Period 1, full elongation | Positive | 0.0029 | 0.2755 |
| Percent total ground cover | Foliar Ca/Zn, Period 1, full elongation | Positive | 0.0285 | 0.1601 |
| Percent total ground cover | Foliar K/Zn, Period 1, full elongation | Negative | 0.0137 | 0.1982 |
| Percent total ground cover | Foliar Ca/Cu, Period 1, full elongation | Positive | 0.0257 | 0.1655 |
| Percent total ground cover | Foliar Ca/Al, Period 2, full elongation | Positive | 0.0011 | 0.3226 |
| Percent total ground cover | Foliar Mg/Al, Period 2, full elongation | Positive | 0.031 | 0.1555 |
| Percent total ground cover | Foliar Ca/Mn, Period 2, full elongation | Positive | 0.0103 | 0.2127 |
| Percent total ground cover | Foliar Ca/Zn, Period 2, full elongation | Positive | 0.0103 | 0.2128 |
| Percent total ground cover | Foliar Ca/Al, Period 3, full elongation | Positive | 0.0126 | 0.2025 |
| Percent total ground cover | Foliar Mg/Al, Period 3, full elongation | Positive | 0.018 | 0.1841 |
| Percent total ground cover | Foliar Ca/Mn, Period 3, full elongation | Positive | 0.0042 | 0.2579 |
| Percent total ground cover | Foliar Mg/Mn, Period 3, full elongation | Positive | 0.0162 | 0.1896 |
| Percent total ground cover | Foliar Ca/Fe, Period 3, full elongation | Positive | 0.0269 | 0.1631 |
| Percent total ground cover | Foliar Mg/Fe, Period 3, full elongation | Positive | 0.0223 | 0.1728 |
| Percent total ground cover | Foliar Ca/Al, Period 4, full elongation | Positive | 0.001 | 0.325 |
| Percent total ground cover | Foliar Mg/Al, Period 4, full elongation | Positive | 0.0033 | 0.2695 |
| Percent total ground cover | Foliar K/Al, Period 4, full elongation | Positive | 0.0182 | 0.1834 |
| Percent total ground cover | Foliar Ca/Mn, Period 4, full elongation | Positive | 0.0331 | 0.1521 |
| Percent total ground cover | Foliar Ca/Fe, Period 4, full elongation | Positive | 0.0217 | 0.1744 |
| Percent total ground cover | Foliar Mg/Fe, Period 4, full elongation | Positive | 0.0441 | 0.137 |
| Percent total ground cover | Foliar Ca/Al, Period 5, full elongation | Positive | 0.0333 | 0.1518 |
| Percent total ground cover | Foliar Ca/Al, Period 5, partial elongation | Positive | 0.0043 | 0.2562 |
| Percent total ground cover | Foliar Mg/Al, Period 5, partial elongation | Positive | 0.0362 | 0.1474 |
| Percent total ground cover | Foliar K/Al, Period 5, partial elongation | Positive | 0.0225 | 0.1725 |
| Percent total ground cover | Foliar Ca/Mn, Period 5, partial elongation | Positive | 0.0009 | 0.3303 |
| Percent total ground cover | Foliar Ca/Fe, Period 5, partial elongation | Positive | 0.0489 | 0.1316 |
| Percent total ground cover | Foliar Ca/Zn, Period 5, partial elongation | Positive | 0.0254 | 0.166 |
| Percent total ground cover | Foliar Ca/Al, Period 6, full elongation | Positive | 0.0358 | 0.148 |
| Forest floor fuels subset: | | | | |
| 1+10-hr fuels | Foliar Ca/Fe, Period 2, full elongation | Positive | 0.0005 | 0.3606 |

| | | | | |
|---|---|---|---|---|
| 1+10-hr fuels | Foliar Mg/Fe, Period 2, full elongation | Positive | 0.0006 | 0.3515 |
| 1+10-hr fuels | Foliar K/Fe, Period 2, full elongation | Positive | 0.0002 | 0.4014 |
| 1+10-hr fuels | Foliar Mg/Cu, Period 5, full elongation | Negative | 0.0129 | 0.2011 |
| 100-hr fuels | Foliar Mg/Cu, Period 1, full elongation | Positive | 0.0253 | 0.1664 |
| 100-hr fuels | Foliar Mg/Mn, Period 2, full elongation | Positive | 0.0127 | 0.2019 |
| 100-hr fuels | Foliar Mg/Fe, Period 2, full elongation | Positive | 0.0005 | 0.3596 |
| 100-hr fuels | Foliar K/Fe, Period 2, full elongation | Positive | 0.0017 | 0.2996 |
| 100-hr fuels | Foliar Ca/Al, Period 6, full elongation | Positive | 0.05 | 0.13 |
| 100-hr fuels | Foliar Mg/Al, Period 6, full elongation | Positive | 0.0096 | 0.2164 |
| 100-hr fuels | Foliar K/Al, Period 6, full elongation | Positive | 0.0166 | 0.1883 |
| 100-hr fuels | Foliar Mg/Mn, Period 6, full elongation | Positive | 0.0343 | 0.1502 |
| 100-hr fuels | Foliar Mg/Fe, Period 6, full elongation | Positive | 0.0221 | 0.1734 |
| 1000-hr fuels | Foliar Ca/Al, Period 1, full elongation | Negative | 0.01 | 0.2141 |
| 1000-hr fuels | Foliar Ca/Mn, Period 1, full elongation | Negative | 0.0048 | 0.2506 |
| 1000-hr fuels | Foliar Ca/Fe, Period 1, full elongation | Negative | 0.0288 | 0.1594 |
| 1000-hr fuels | Foliar Ca/Al, Period 2, full elongation | Negative | 0.0244 | 0.1682 |
| 1000-hr fuels | Foliar Ca/Mn, Period 2, full elongation | Negative | 0.0113 | 0.2081 |
| 1000-hr fuels | Foliar Ca/Al, Period 3, full elongation | Negative | 0.0284 | 0.1602 |
| 1000-hr fuels | Foliar Ca/Mn, Period 3, full elongation | Negative | 0.007 | 0.2324 |
| 1000-hr fuels | Foliar K/Al, Period 4, full elongation | Negative | 0.0147 | 0.1947 |
| 1000-hr fuels | Foliar Ca/Zn, Period 5, partial elongation | Negative | 0.0474 | 0.1332 |
| 1000-hr fuels | Foliar K/Zn, Period 5, partial elongation | Negative | 0.001 | 0.3274 |
| Total fuels | Foliar Ca/Fe, Period 2, full elongation | Positive | 0.0006 | 0.3472 |
| Total fuels | Foliar Mg/Fe, Period 2, full elongation | Positive | 0.0001 | 0.5498 |
| Total fuels | Foliar K/Fe, Period 2, full elongation | Positive | 0.0001 | 0.5499 |
| Total fuels | Foliar Mg/Cu, Period 5, full elongation | Negative | 0.0398 | 0.1424 |
| Total fuels | Foliar K/Cu, Period 5, full elongation | Negative | 0.0444 | 0.1366 |
| Total fuels | Foliar K/Zn, Period 5, partial elongation | Negative | 0.0304 | 0.1567 |
| Soil influences subset: | | | | |
| Soil Ca/Al | Foliar Ca/Al, Period 5, partial elongation | Positive | 0.0244 | 0.1682 |
| Soil Mg/Al | Foliar Mg/Al, Period 1, full elongation | Positive | 0.0132 | 0.1999 |
| Soil Mg/Al | Foliar Mg/Al, Period 5, partial elongation | Positive | 0.0033 | 0.2686 |
| Soil K/Al | Foliar K/Al, Period 1, full elongation | Positive | 0.0086 | 0.2219 |
| Soil K/Al | Foliar K/Al, Period 3, full elongation | Positive | 0.011 | 0.2092 |
| Soil K/Al | Foliar K/Al, Period 5, partial elongation | Positive | 0.0403 | 0.1417 |
| Soil Mg/Mn | Foliar Mg/Mn, Period 2, full elongation | Positive | 0.0484 | 0.132 |
| Soil Mg/Mn | Foliar Mg/Mn, Period 4, full elongation | Positive | 0.0042 | 0.2577 |
| Soil Mg/Mn | Foliar Mg/Mn, Period 5, partial elongation | Positive | 0.0336 | 0.1514 |

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

**Table 7:** 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].

| Independent variable | Dependent variable | Correlation | Model p-value | $r^2$ |
|---|---|---|---|---|
| Basal area | Soil Ca/Al | Negative | 0.0482 | 0.1308 |
| Basal area | Soil Mg/Al | Negative | 0.0472 | 0.1317 |
| Basal area | Soil K/Al | Negative | 0.0486 | 0.1303 |
| Total tree count | Soil Ca/Al | Negative | 0.0481 | 0.1347 |
| Total tree count | Soil K/Al | Negative | 0.0451 | 0.1425 |
| Percent total ground cover | Soil Ca/Fe | Positive | 0.046 | 0.1323 |
| Percent total ground cover | Soil Mg/Cu | Negative | 0.0482 | 0.1316 |
| Percent total ground cover | Soil K/Cu | Negative | 0.006 | 0.24 |
| 1+10-hr fuels | Soil K/Fe | Negative | 0.0458 | 0.1319 |
| 100-hr fuels | Soil Mg/Cu | Positive | 0.0489 | 0.1341 |
| 1000-hr fuels | Soil K/Cu | Positive | 0.0184 | 0.183 |
| Percent sand | Soil Ca/Al | Negative | 0.0476 | 0.1307 |
| Percent sand | Soil Mg/Al | Negative | 0.0497 | 0.1306 |
| Percent sand | Soil Ca/Mn | Negative | 0.0487 | 0.1309 |
| Percent sand | Soil Mg/Mn | Negative | 0.001 | 0.3253 |
| Percent sand | Soil Ca/Fe | Negative | 0.0099 | 0.215 |
| Percent sand | Soil Mg/Fe | Negative | < 0.0001 | 0.4433 |
| Percent sand | Soil Mg/Zn | Negative | 0.0468 | 0.1338 |

| | | | | |
|---|---|---|---|---|
| Percent sand | Soil Mg/Cu | Negative | 0.0144 | 0.1955 |
| Percent silt | Soil Ca/Mn | Positive | 0.0049 | 0.2497 |
| Percent silt | Soil Mg/Mn | Positive | 0.0004 | 0.3611 |
| Percent silt | Soil K/Mn | Positive | 0.0243 | 0.1684 |
| Percent silt | Soil Ca/Fe | Positive | 0.0297 | 0.1578 |
| Percent silt | Soil Mg/Fe | Positive | 0.0063 | 0.2374 |
| Percent silt | Soil Ca/Zn | Positive | 0.0146 | 0.195 |
| Percent silt | Soil Mg/Zn | Positive | 0.0022 | 0.2884 |
| Percent silt | Soil Ca/Cu | Positive | 0.0372 | 0.1459 |
| Percent silt | Soil Mg/Cu | Positive | 0.0151 | 0.1933 |
| Percent clay | Soil Ca/Al | Positive | 0.0202 | 0.1782 |
| Percent clay | Soil Mg/Al | Positive | 0.0143 | 0.196 |
| Percent clay | Soil K/Mn | Negative | 0.0071 | 0.2315 |
| Percent clay | Soil Mg/Fe | Positive | 0.0028 | 0.2774 |
| Percent clay | Soil K/Fe | Negative | 0.0029 | 0.2748 |
| Percent clay | Soil K/Zn | Negative | 0.0126 | 0.2025 |
| Percent clay | Soil K/Cu | Negative | 0.0002 | 0.3919 |
| Soil pH | Soil Ca/Al | Positive | 0.0453 | 0.1341 |
| Soil pH | Soil Ca/Mn | Positive | 0.0011 | 0.3225 |
| Soil pH | Soil Mg/Mn | Positive | 0.0477 | 0.1313 |
| Soil pH | Soil K/Mn | Positive | 0.0481 | 0.1305 |
| Soil pH | Soil Ca/Fe | Positive | 0.0012 | 0.3154 |
| Soil pH | Soil Ca/Zn | Positive | 0.047 | 0.1319 |

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

**Table 8:** 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].

comparatively high values in site trees residing in stand portions that had been neither thinned nor burned were readily apparent in Ca/Al and Mg/Al, and to a somewhat lesser degree in K/Al although in this case the distinction was shared with the unburned whole-tree treatment combination which shared eminence once regarding Ca/Al as well, while there was also some propensity demonstrated toward higher values in unburned stand portions generally. Furthermore, the lowest values for each of these ratios occurred almost universally in the burned portions of either the cut-to-length or whole-tree subunits and were frequently comparable therein, which was of possible consequence given the diminished growth and elevated mortality prevailing in these two treatment combinations as documented previously in Swim et al. [32,34], respectively. Molar Ca/Al especially has been proposed as potentially prognostic regarding excessive metal uptake in forest trees with a tentative threshold value in foliar tissues considered indicative of potential phytotoxicity of ≤ 12.5 [16], and the burned cut-to-length combination was below this value in Period 3 and both this and the burned whole-tree combination only marginally exceeded it at multiple samplings. Several seemingly incongruent regression models portrayed Ca/Al mostly, but also K/Al once, to be negatively related to total tree count, which would appear illogical given the felling inherent in the burned cut-to-length and burned whole-tree combinations where these ratios were lowest, but in fact these two combinations had the highest tree counts at the study site [32] owing to the prevalence there of trees <20.3 cm DBH, which as noted previously were generally excluded from harvest. Nevertheless, numerous other models revealed each of the ratios involving Al to be negatively correlated with bole char circumference and positively correlated with both total ground cover and 100-hr fuel loading, relationships consistent with the finding that unburned stand portions generally produced higher values. The relative abundance of understory vegetation and 100-hr fuels in the unburned stand portions of the study site is readily apparent in data presented in Salverson et al. [31] and Swim et al. [32], respectively. In a prior study concerned with wildland fire influences on Sierran forest nutrition [35], a depression of Ca/Al in Jeffrey pine by a wildfire was disclosed that persisted through multiple samplings over two growing seasons. Of the ratios involving Mn, each somewhat paralleled the Al based ratio featuring the same base cation, although the prominence of the unthinned and unburned treatment combination diminished considerably in later samplings for Ca/Mn when the burned portion of this thinning treatment along with the unburned whole-tree combination shared eminence, was inconsistent for Mg/Mn with the unburned whole-tree and burned but unthinned combinations also each emergent at single samplings, and was supplanted by the latter combination regarding K/Mn although the unburned whole-tree treatment was again prominent in this case. Nevertheless, the burned portions of the cut-to-length and whole-tree subunits were again conspicuous in the frequency with which the lowest values for these ratios resided therein, although occasionally comparable values were found in the unburned cut-to-length combination, and with the high total tree counts in the two former combinations, as previously noted, only marginally surpassing that in the latter [32], the frequent negative correlations between Ca/Mn and these counts along with the single one involving K/Mn suggest that these can be added to Ca/Al and K/Al as ratios that may have been depressed by higher stand density as quantified by this measure. Also common were positive correlations between ratios involving Mn and total ground cover, especially Ca/Mn, while two models revealed such relationships between Mg/Mn and 100-hr fuels, which corroborates that burning may not have been conducive to generating higher values for them as was the case regarding the ratios involving Al. Multiple negative relationships between Ca/Mn and 1000-hr fuels, and similarly between Ca/Al and them, were likely reflective of the comparative abundance of these fuels in the burned and unburned portions of the cut-to-length subunit along with their third highest loading in the burned whole-tree treatment [32].

As for the ratios incorporating Fe, the prominence of the unthinned and unburned combination concerning high values receded further from that prevailing in ratios based on Al and even Mn, as did that of the burned but unthinned and unburned whole-tree combinations in Mn based ones, while nearly as often as not, low values were found in other than the burned portions of the cut-to-length or whole-tree subunits or the unburned cut-to-length treatment. Thus, the tendency for high ratios involving Al and Mn to reside in the unthinned treatment over the course of the study with low ones predominantly in burned stand portions was much less pronounced where Fe based ratios were concerned. This was reflected in regression models that, although moderately numerous and encompassing those with mensurational, fire injury, ground cover, and fuels factors as independent variables, were often difficult to reconcile with the responses to treatment. However, of these, positive relationships between Ca/Fe in Periods 1, 3, and 4 along with Mg/Fe at the latter two samplings and ground cover coincided with occasions when the highest values for each occurred in the unthinned and unburned combination, possibly again indicating that attainment of higher ratios was sometimes facilitated by the absence of both thinning and fire given that understory vegetation was most abundant in this stand where neither was implemented [31]. Additional evidence supporting such a presumption about the fire influence may have been supplied by the positive correlations between Ca/Fe, Mg/Fe, and K/Fe and total fuels in Period 2 when the highest value of each occurred in the unburned cut-to-length treatment where the greatest total loading was found as well [32]. Comparatively, ratios with Zn as the metallic component were little affected by treatment, especially Mg/Zn for which significant differences among the various treatment combinations were limited to the last two samplings, although some semblance of consistency was displayed then as the burned cut-to-length combination produced the highest value at both. This treatment combination also produced the highest value for Ca/Zn at the final sampling, but beforehand the high value was found in either the burned or unburned portions of the unthinned subunit, once for the former and twice for the latter. The fire treatment influence on K/Zn was the most apparent effect exerted within this group, as its highest value occurred in a burned stand portion at five of the six samplings although with two residing in the cut-to-length subunit and three in the unthinned treatment. Coinciding with the high Ca/Zn values of the unthinned and unburned combination in Period 1 and 2 were regression models featuring positive correlations between this ratio and ground cover, which as previously noted was most abundant therein of all of the treatment combinations, while another model disclosed a positive relationship between K/Zn in Period 6, one of the samplings at which its highest value occurred in the burned cut-to-length treatment, and bole char circumference. Based on the proportion of sampling periods within which significant differences prevailed, the ratios least affected by treatment were those involving Cu, most apparently Ca/Cu for which such disparities were confined to two samplings at which its highest values were split between the unburned portion of the unthinned subunit and the burned portion of the cut-to-length subunit. Otherwise, only for Mg/Cu was the high value found in the same treatment twice, specifically in the burned portion of the cut-to-length subunit, while at two other samplings it occurred in the unburned portions of either the unthinned or whole-tree treatments, and regarding K/Cu, high values were dispersed among the burned and unburned whole-tree combinations along with the burned but unthinned and burned cut-to-length combinations. Molar Mg/Cu was also the one in this group for which plausible commonalities between treatment responses and regression models were most prevalent, specifically in Period 5 when this ratio was positively correlated with bole char height, expressed on either an absolute or percentage basis, and negatively related to both 1+10-hr and total fuels, as prevailing in the burned portion of the cut-to-length subunit were the highest site tree Mg/Cu and char height and percentage along with the second lowest fine and total fuel loading [32].

Aside from the various treatment influences on the foliar ratios investigated here, it was apparent that when the averages within sampling periods were compared across them, patterns emerged for some 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. Specifically, each of the three molar ratios involving Al generally increased as the study progressed, but contrarily, Ca/Mn and Ca/Zn decreased with the transition much more abrupt in the former than the latter. It has been documented that foliar nutrient concentrations can fluctuate with annual variation in precipitation [14], while results here extend this axiom to include multiple base cation to metallic element ratios albeit with clear disparities evident in their responses. Another form of variation in some other ratios, 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 conducted. Specifically, K/Mn, K/Zn, and K/Cu were relatively low repeatedly in the early portion of the season and high in the late portion. Mechanistic interpretation of this pattern, particularly regarding growth implications, is complicated by the fact that because it is based on concentrations in fully elongated needles, early 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 the molar ratios although with a dichotomy in its influence readily apparent, as Ca/Al, Ca/Fe, Ca/Zn, and Ca/Cu were mostly higher in mature needles, Mg/Fe and Mg/Cu were higher in them as well but Mg/Mn especially and Mg/Al generally were higher in young ones instead, and each of the five ratios involving K was likewise higher in the latter. In part, these findings probably reflect the relative mobility of the base cation components of the ratios and thus their propensity toward translocation from older, senescing needles to younger, actively growing tissues, thereby ultimately diminishing in concentration as needles age, with Ca recognized as largely immobile while Mg and especially K are considered to be readily translocated in most plants [36,37]. Regardless, apart from foliar age considerations and specific to the ratios in immature needles, negative correlations between all of those involving Al and bole char circumference and positive ones between them and total ground cover, along with additional positive relationships between the rest of the ratios based on Ca and the latter except for Ca/Cu, suggest that the underburn was not conducive to higher values for many of the ratios in general.

In stark contrast to the wide array of foliar ratios significantly affected by either the thinning or fire treatments, and in several cases both, detection of such on those in the soil was severely limited. As Ca/Al has been the focus of studies involving forest nutrition from the viewpoint of the interrelationships between base cations and metallic elements [16], the lack of a definitive thinning or fire effect on this ratio, and to the extent that any disparities among the treatment combinations existed the location of the highest overall value in the unburned portion of the whole-tree subunit, is perhaps the most notable of the findings from the soil component of this study. In research somewhat comparable in scope albeit with wildfire replacing controlled burning, Thiffault et al. [38] reported that forest floor Ca/Al was depressed by thinning a boreal coniferous stand in comparison to that resulting from fire, but the disagreement between their finding and that here may reflect in part that the focus here was the upper mineral portion of the soil profile. Regardless, unambiguous significant effects on soil ratios in this study were limited to two, a thinning effect on Ca/Fe manifested in higher values in the unthinned subunit generally and especially in its unburned portion, and a fire effect on K/Cu evident in higher overall values in burned stand portions with the disparity most pronounced in the unthinned treatment. Two regression models featuring total ground cover as the independent variable provided some confirmation of the treatment influences on these two ratios, one with Ca/Fe in a positive relationship and the other with K/Cu in a negative one, reflecting the abundance of understory vegetation in the unburned portion of the unthinned subunit and its reduction by the underburn irrespective of thinning treatment [31] regarding the former and latter, respectively. Nevertheless, and despite the aforementioned scarcity of significant treatment effects, other independent variables were more prominent in the regression analysis concerning the molar ratios in soil, including the density variables of basal area and total tree count to which several ratios incorporating Al as the metallic component were negatively related, and soil pH with which ratios featuring nearly all of the metallic elements in at least one significant model were positively correlated. Most prominent in this regard, however, was soil texture, as a wide assortment of ratios were negatively related to percent sand and positively related to percent silt while both positive and negative correlations prevailed in nearly equal proportion with percent clay serving as the independent counterpart. Also somewhat removed from the direct examination of the thinning and fire treatment influences that constituted the main focus here was the integration of soil and foliar nutrition through regression models that relied upon the former and later as independent and dependent variables, respectively. Several of these models proved to be significant, although in general they explained no more than the modest amount of the variation in the dependent components that characterized many of the other models included in the study. Most prevalent were those individually matching K/Al and Mg/Mn in soil and foliage while other ratios involving Al were represented as well, and all featured positive correlations. Interrelating foliar nutrition to that in the soil of western USA forest types has been problematic [39,40] although a previous study with Jeffrey pine and California white fir (*Abies concolor* var. *lowiana* [Gord.] Lemm.) on an eastern Sierran site [35] revealed some such connections which have been augmented here for the former species regarding base cation to metallic element ratios.

In summary, this study was concerned with mineral nutrition in a pure, eastern Sierran, uneven-aged Jeffrey pine stand subjected to thinning and prescribed fire restoration treatments, with the former entailing both cut-to-length and whole-tree harvesting approaches and the latter consisting of spring season underburning. An unthinned stand subunit and unburned stand portions distributed across the three thinning treatments provided additional bases for comparison. Focused on an array of base cation to metallic element molar ratios and encompassing six samplings over multiple growing seasons of fully elongated needles from site trees selected for their overall superiority, a propensity was revealed for Ca/Al, Mg/Al, K/Al, Ca/Mn, Mg/Mn, and K/Mn to be higher in the unthinned treatment and lower in burned stand portions. Temporal patterns emerged when some ratios were averaged across treatments, including higher Ca/Al, Mg/Al, and K/Al in wetter portions of the study, which was conducted in a prolonged drought, while Ca/Mn and Ca/Zn were higher under the most severe drought conditions. Also, K/Mn, K/Zn, and K/Cu were generally lower in the early portion of the growing season than the late portion. As determined from a single mid growing season sampling at which both previous and current year needles were collected, Mg/Al, K/Al, Mg/Mn, K/Mn, K/Fe, K/Zn, and K/Cu were generally higher in the younger needles while Ca/Al, Ca/Fe, Mg/Fe, Ca/Zn, Ca/Cu, and Mg/Cu were higher in older ones. Sampled near the midpoint of the study, mineral soil Ca/Fe was higher in the unthinned subunit generally, especially in its unburned portion, while K/Cu was higher overall in burned stand portions with the disparity most pronounced in the unthinned subunit. These findings promote understanding of the nutritional alterations involving the interrelationships between base cations and metallic elements that occur in Jeffrey pine and similar forests types subjected to increasingly common management practices.

## Acknowledgements

Support for this research was provided by the Nevada Agricultural Experiment Station, McIntire-Stennis Cooperative Forestry Research Program, and the USDA Forest Service. The authors thank Brunson D, Chacon J, Fernandez G, Frederick W, Gunder T, Holcomb J, Jones K, McCarthy C, Melville B, Murphy K, Roubique J, Salas R, Schall G, Shane R, Spurlock J, Wallace A and Robinson Enterprises Inc. for their assistance.

## References

1. Smith DM (1962) The practice of silviculture. 7th edn. John Wiley and Sons, New York, NY, USA.
2. Daniel TW, Helms JA, Baker FS (1979) Principles of silviculture. 2nd edn. McGraw-Hill, New York, NY, USA.
3. Coulson RN, Witter JA (1984) Forest entomology: Ecology and management. John Wiley and Sons, New York, NY, USA.
4. Wood DL, Stark RW, Waters WE, Bedard WD, Cobb Jr FW (1985) Treatment tactics and strategies. In Integrated pest management in pine-bark beetle ecosystems. Waters WE, Stark RW, Wood DL (eds.). John Wiley and Sons, New York, NY, USA, pp: 121-139.
5. 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.
6. Stephens SL (2005) Forest fire causes and extent on United States Forest Service lands. International Journal of Wildland Fire 14: 213-222.
7. Westerling AL, Hidalgo HG, Cayan DR, Swetnam TW (2006) Warming and earlier spring increase western US forest wildfire activity. Science 313: 940-943.
8. 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.
9. Williams J (2013) Exploring the onset of high-impact mega-fires through a forest land management prism. Forest Ecology and Management 294: 4-10.
10. Pyne SJ, Andrews PL, Laven RD (1996) Introduction to wildland fire. 2nd edn. John Wiley and Sons, New York, NY, USA.
11. Wright HA, Bailey AW (1982) Fire ecology: United States and southern Canada. John Wiley and Sons, New York, NY, USA.
12. DeBano LF, Neary DG, Folliott PF (1998) Fire's effects on ecosystems. John Wiley and Sons New York, NY, USA.
13. Husari S, Nichols HT, Sugihara NG, Stephens SL (2006) Fire and fuel management. In Fire in California's ecosystems (Sugihara NG, van Wagtendonk JW, Shaffer KE, Fites-Kaufman JA, Thode AE eds.). University of California Press, Berkeley, CA, USA, pp. 444-465.
14. Fisher RF, Binkley D (2000) Ecology and management of forest soils. 3rd edn. John Wiley and Sons, New York, NY, USA.
15. Kozlowski TT, Kramer PJ, Pallardy SG (1991) The physiological ecology of woody plants. Academic Press, New York, NY, USA.
16. Cronan CS, Grigal DF (1995) Use of calcium/aluminum ratios as indicators of stress in forest ecosystems. Journal of Environmental Quality 24: 209-226.
17. USDA Forest Service (1994) Soil survey of the Tahoe National Forest area, California. USDA Forest Service Pacific Southwest Region, San Francisco, CA, USA.
18. 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.

19. 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.
20. Nyland RD (2002) Silviculture: Concepts and applications. 2nd edn. McGraw-Hill, New York, NY, USA.
21. Curtis RO, Marshall DD (2000) Why quadratic mean diameter? Western Journal of Applied Forestry 15: 137-139.
22. Davis LC, Johnson KN, Bettinger PS, Howard TE (2001) Forest management. 4th edn. McGraw-Hill, New York, NY, USA.
23. 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.
24. 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.
25. Avery TE, Burkhart HE (2002) Forest measurements. 5th edn. McGraw-Hill, New York, NY, USA.
26. 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.
27. 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.
28. Klute A (1986) Methods of soil analysis: Part 1. Physical and mineralogical methods. 2nd edn. American Society of Agronomy, Madison, WI, USA.
29. 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.
30. 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.
31. Salverson WG, Walker RF, Fecko RM, Frederick WB, Johnson DW, Miller WW (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.
32. 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.
33. 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. Journal of Forest Research 5: 172.
34. 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.
35. 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.
36. Kramer PJ, Kozlowski TT (1979) Physiology of woody plants. Academic Press, New York, NY, USA.
37. Pallardy SG (2008) Physiology of woody plants. 3rd edn. Academic Press, New York, NY, USA.
38. Thiffault E, Belanger N, Pare D, Munson AD (2007) How do forest harvesting methods compare with wildfire? A case study of soil chemistry and tree nutrition in a boreal forest. Canadian Journal of Forest Research 37: 1658-1668.
39. 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.
40. 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.