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Long-Term Growth of Sierra Nevada Mixed Conifer in Response to Mechanized Thinning, Slash Mastication, and Prescribed Fire

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Abstract

Thinning implemented with a cut-to-length system accompanied by on-site slash mastication and dispersal and followed by prescribed underburning were evaluated for their influences on individual tree and stand level growth in eastern Sierran mixed conifer. California white fir (*Abies concolor* var. *lowiana* [Gord.] Lemm.) dominated stand composition with Jeffrey pine (*Pinus jeffreyi* Grev. & Balf.) and sugar pine (*Pinus lambertiana* Dougl.) moderately represented while incense-cedar (*Libocedrus decurrens* Torr.) and California red fir (*Abies magnifica* A. Murr.) were exceedingly minor constituents. One decade after treatment, trees in the thinned stand subunit exhibited large height and DBH gains irrespective of fire treatment, responses attributable to the thinning protocol and to enhanced growth of residual stems, while minimal dimensional changes prevailed in the unthinned subunit. Diminished board feet and cubic volumes prevailed in the thinned subunit, and especially in its burned portion, through the end of the study, however, reflecting a reduction in stocking exacerbated by further loss caused by the underburn. Steep reductions in white fir volumes were responsible for the overall losses in the thinned and burned treatment combination. Jeffrey pine responded favorably to thinning but not to underburning, while sugar pine volume responses were unaffected by either treatment.

Keywords: Stand density management; Cut-to-length harvesting; Prescription fire; Tree dimensions; Stand volume; *Abies concolor; Pinus jeffreyi; Pinus lambertiana; Libocedrus decurrens; Abies magnifica*

Introduction

The responses of forest stands of mixed composition to silvicultural practices are a composite of the capacities of the individual species to react to the changes induced in their environment, which in turn reflects their silvical features and especially those directly pertinent to the competition for resources with the other species in the mixture, all of which is influenced by their relative adaptability to the site that the stand occupies. A prominent example of such composition in western USA forests is Sierra Nevada mixed conifer, which includes a variant at mid elevations on the eastern slopes featuring California white fir, Jeffrey pine, incense-cedar, and sugar pine sometimes augmented with occasional California red fir where cold air drainage is prevalent [1]. The silvics of these species differ sharply, and perhaps none of the differences are more profound than that entailing shade tolerance with white fir the most tolerant overall although supposedly it is only marginally more so than red fir, Jeffrey pine the least tolerant, and incense-cedar and sugar pine considered to be intermediate regarding this characteristic [2]. The tolerance of white fir is reflected in an ability to regenerate profusely and then persist in the shade of an overstory canopy greatly exceeding that of the other constituents in this cover type, which contributes to a propensity for it to increasingly dominate the composition of many mixed conifer stands [3,4], but it also accounts for its ability to endure prolonged periods in a lower canopy position but then respond dramatically when released from competition [5]. Another prominent silvical distinction is rooting depth, with Jeffrey pine especially noted for its large taproot that permits access to scarce resources, principally water, available in deeper soil strata, rendering it well adapted to dry forest sites [6]. Sugar pine and incense-cedar are also endowed with well-developed root systems [7,8]. In contrast, white fir and red fir rooting depth is relatively limited, especially on sites with shallow soils [5,9], making them susceptible to moisture stress and thus less well adapted to drier substrates. It logically follows that these firs should benefit somewhat more from reduced competition for water, such as that effected by downward adjustment in stocking levels, than the other species in this cover type, but rooting limitations that are manifested in marginal adaptation to drier sites are a liability with profound consequences in a scenario involving a possible change in climate to a drier precipitation regime [10]. Other silvical differences among the species noted above include marked disparities in their fire adaptation, as Jeffrey pine is recognized for its fire resistance [11] owing to its propensity to self-prune readily, which reduces the tendency to torch when exposed to surface fire, and the thermal protection provided by its thick bark, which develops at a relatively young age [3,12]. At the other extreme, white fir has a pronounced susceptibility to injury due to delayed self-pruning, lateness of thick bark development, and copious production of highly flammable pitch [3,11-14]. Comparatively, the insulating qualities of sugar pine and incense-cedar bark are close to that of Jeffrey pine [15,16] although both are somewhat slow to self-prune [7,8], while red fir is comparable to white fir in that neither self-pruning nor bark development proceed at the pace assumed to impart fire resistance until late age is achieved [17]. Although fire adaptation is often evaluated on the basis of relative wildfire resistance, it in fact is also a consideration in assessing the potential impacts of prescribed fire on overall stand health and performance, as controlled burning frequently causes both crown loss and cambial damage to varying extent even when implemented under exacting prescription conditions.

Presented here is an assessment of the influences of mechanized thinning with subsequent slash mastication and prescriptive underburning on individual tree and stand level growth in an eastern Sierran mixed conifer stand over the long term. Included is an examination of possible linkages between selected tree and stand level variables quantified at pertinent junctures over the course of study.

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Materials and Methods

Study site and stand

The stand selected for study is naturally regenerated, second growth, uneven-aged Sierra Nevada mixed conifer located on the USDA Forest Service Lake Tahoe Basin Management Unit (39.22° N, 120.10°W). Approximately 8.1 ha in size, the site is at 2050 m elevation, the aspect is generally east, and the slope averages 7%. With snowfall predominating, mean annual precipitation has been 80 cm during the past century, but over the course of this study the annual average was 78 cm [18]. The soils are of the Jorge-Tahoma Association, derived from volcanic parent material, and exceedingly rocky [19]. Based on dominant crown class trees averaging 162 years in age [20], the site quality is class IV according to the Dunning [21] site classification system for Sierra Nevada mixed conifer. Ownership of the site was transferred from the private to the public sector approximately two decades before this study commenced, and prior to the treatment implementation detailed below, the stand reflected a legacy of prolonged fire exclusion and periodic harvests targeting its yellow and white pine components.

Treatment installation

In September 2002, the study site was divided into two subunits of equal proportion with one of two thinning treatments randomly assigned to each subunit, specifically a cut-to-length harvest accompanied by slash mastication or an unthinned control without any surface fuel treatment. In June 2003, the mechanized harvesting and slash treatments were implemented, with the former entailing the use of a Rottne SMV Rapid EGS 6WD single-grip harvester coupled with a Rottne SMV Rapid RK-90 6WD self-loading forwarder (Rottne Industri AB, Rottne, Sweden). The cut-to-length system retains residual organic materials in the stand as slash mats created by the harvester through its delimbing and topping functions that both the harvester and forwarder subsequently travel over and is designed to minimize mineral soil impacts [20]. Other than a contractual stipulation that harvested trees not exceed 50.8 cm DBH, preferentially consist of white fir as available, and completely exclude live sugar pine, operator choice was exercised in the selection of those to be removed to achieve a target residual basal area of 30 $m^2 ha^{-1}$, but the contractor was not obligated to remove stems of<20.3 cm DBH. Immediately following the thinning, the resulting slash mats were masticated and redistributed using a Morbark 30/36 Mountain Goat self-propelled chipper (Morbark, Inc., Winn, MI, USA), with the directive to also treat preexisting coarse woody debris where the operator considered it to be excessive and to distribute chipped materials evenly over the thinned subunit.

With the portion to be treated randomly chosen, a controlled underburn was implemented on one-half of each of the two subunits dedicated to the individual thinning treatments in early June of 2004. Partitioning of each subunit was accomplished using 1.0-m-wide hand lines accompanied by the manual felling of trees with crowns overtopping the fuel breaks as needed for containment. A strip head fire ignition pattern was employed starting at 0800 hrs and the underburn was completed at 1400 hrs with the designated portions of both subunits treated in a single day. At ignition, the air temperature was 10°C, relative humidity was 45%, the wind speed was 4.8 km hr^{-1}, and 10-hr timelag fuel moisture was 18%. The rate of spread averaged approximately 57 m hr^{-1} over the entire burn period, and at the close of ignition, the air temperature was 16°C, relative humidity was 23%, and the wind speed was 9.6 km hr^{-1}.

Data collection

During the designation of the subunits in September 2002, 20 permanent 0.04 ha circular plots were established for measurement of mensurational variables with 10 plots located in each of the two subunits, and within each subunit, five in the portion to be burned with the remaining five in the portion to remain unburned. All trees ≥ 20.3 cm DBH in every plot were measured for total height, DBH, and live crown length and then tallied by species, and included were free standing dead trees, defined as those with no live crown, tallied accordingly. Subsequently, tree counts were summed by plot as were dead stems, and the percentages of the latter were calculated as well. Also, tree heights and live crown lengths were used to calculate live crown percentages, average DBH values by plot were calculated using the quadratic mean formula [22], and basal area by plot was derived from plot stem counts and quadratic mean DBH [23]. Ultimately, the stem counts and basal areas for each plot were expanded to reflect equivalent 1.0 ha values.

For volume determination, three measures were used, specifically board feet volume, cubic feet volume, and cubic meter volume, with board feet and cubic feet units those most commonly used in the USA while cubic meter units are most common where the metric system prevails [24]. Preliminary volume determinations were species specific regardless of the units used. White fir, sugar pine, and incense-cedar board feet and cubic feet volumes were derived from the McDonald & Skinner [25] tables, which rely upon DBH measurements exclusively for volume determination. Jeffrey pine and red fir volumes were based on the USDA Humboldt-Toiyabe National Forest board and cubic feet tables [26], which incorporate both tree height and DBH in volume determinations. For all of the tables identified above, utilization extends to a merchantable top diameter of six inches, while for the board feet measure all pertinent tables reflect the Scribner Decimal C log rule. Cubic meter volume for each species was derived by direct conversion of cubic feet volume. Once the tree volumes of individual species were obtained, they were summed by plot and then combined across species within each plot. Ultimately, plot volumes based on board feet and cubic feet were expanded to reflect equivalent 1.0 ac values while those for cubic meters were further expanded to reflect a 1.0 ha equivalent value.

Two additional inventories identical to that detailed above in all respects were conducted in September of 2005 and of 2012, with all extrapolated values regarding tree dimensions, density, mortality, and volume again calculated following each one. The availability of data from each of these three inventories permitted the calculation of the changes in all variables at critical intervals over the course of the study.

Statistical analysis

Because field logistics involving the implementation of the mechanized and prescribed fire treatments necessitated that the former be assigned to individual subunits of the stand with the latter then assigned to one-half of each subunit, it was necessary to test for the independence of the plots within each treatment combination. This was accomplished by calculating residual values, defined as the difference between the mean for a given variable of the five plots for each treatment combination and the values obtained from the individual plots for the selected variable. Subsequently, the residual value of one plot was designated as the independent variable and that of the immediately adjacent plot the dependent variable which was repeated sequentially within each treatment combination yielding one value of each for each plot pair, four values of each for each of the four individual treatment combinations, and thus a total of 16 values of each for the entire stand. These values were then incorporated into simple linear regression models by variable, with the selected variables consisting of pretreatment tree height, DBH, and basal area. Models were considered to be significant, signifying a lack of independence among the plots within treatment combinations, only when $p \leq 0.05$ according to the F-test. None of the models proved to be significant, indicating that responses from individual plots were not significantly influenced by those from immediately adjacent plots for any of these variables.

Data pertaining to tree dimensions, density, mortality, and volume derived from the three stand inventories were analyzed using repeated measures, mixed model analysis of variance (ANOVA) to test for effects of thinning and prescribed fire treatments, the year of inventory, and all possible interactions. This analysis incorporated both the compound symmetry covariance structure and the first-order autoregressive structure, and for a given variable, the covariance structure relied upon was that providing the lowest value for Akaike's Information Criterion (bias-corrected version, AICC). Changes between inventories pertaining to the various study components were subjected to two-way ANOVA for purposes of testing for thinning and fire treatment effects plus their interaction. In every ANOVA indicated above, main effects and their interactions 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 α=0.05.

Additional statistical analysis consisted of two series of simple linear regression models computed to examine possible linkages between variables matched on the basis of plausible relatedness. The first series, hereafter denoted as the crown development series, consisted of models incorporating all possible combinations of live crown length and percentage as independent variables with tree height and DBH, stand basal area and total tree count, dead tree count and percentage, and stand board feet, cubic feet, and cubic meter volumes by species and combined across species, serving as the dependent variables. These were configured such that values of the independent and dependent variables were matched within inventories but also such that the value of the dependent component was drawn from a later inventory. In the latter case, the dependent variables noted above were augmented with live crown length and percentage. The stand density series, the second of the two, was configured exactly the same as the first series except that stand basal area and total tree count replaced the live crown measures as independent variables with the latter subsequently added to the array of dependent variables, and density measures served as the dependent components only when their values from later inventories were paired with those from earlier ones. For both series, regression models were considered significant only when $p \leq 0.05$ according to the F test. All statistical analyses were performed using SAS Version 9.3 (SAS Institute, Inc., Cary, NC).

Results

Species composition, tree dimensions, and stand density

At the 2002 inventory, and thus prior to treatment implementation, the stand consisted of 73.9% white fir, 11.7% Jeffrey pine, and 6.8% sugar pine with incense-cedar and red fir each constituting 3.8%. In 2005, it consisted of 73.4% white fir, 10.6% Jeffrey pine, 10.1% sugar pine, 4.7% incense-cedar, and 1.2% red fir. The final inventory in 2012 revealed a composition of 72.6% white fir, 10.3% Jeffrey pine, 9.7% sugar pine, 5.1% incense-cedar, and 2.3% red fir.

When averaged across species, ANOVA revealed that total tree height was significantly influenced by the year of inventory and the thinning treatment × year of inventory interaction (both p<0.0001) while the changes in height between the 2002 and 2005 inventories and between the former and the 2012 inventory were influenced (both p<0.0001) by the thinning treatment in and of itself (Table 1). Initially, the LSD test indicated that tree height in the burned portion of the unthinned subunit was significantly exceeded by that in its unburned portion with the heights in the two portions of the thinned subunit of intermediate value, but by 2005 that in the burned but unthinned combination was exceeded by the heights in the thinned subunit irrespective of fire treatment, disparities that were again extant at the 2012 inventory. Regarding the change in height, increases in both portions of the thinned subunit from 2002 to 2005 contrasted against decreases in both for the unthinned subunit, while from the initial to the final inventory, even more substantial increases in the thinned subunit irrespective of fire treatment contrasted against a marginal increase in the burned portion of the unthinned treatment and a small decrease in its unburned portion. For both of these time intervals, the LSD test identified as significant the discrepancies in height growth between those in the thinned and unthinned subunits regardless of fire treatment. With respect to DBH, ANOVA again identified the inventory year and the thinning treatment × inventory year interaction as significant influences (both p<0.0001), but along with a thinning treatment effect on the changes from 2002 to 2005 and from 2002 to 2012 (both p<0.0001) it denoted its effect on the change from 2005 to 2012 as significant (p=0.0086) as well. Differences divulged as significant by the LSD test for this dimension consisted of a smaller value in the thinned but unburned combination than in the unthinned and unburned combination in 2002 along with a lower one in the burned but unthinned combination than in the thinned and burned combination in 2012. Additionally, and specific to the changes in DBH, disparities between positive values in the thinned subunit and negative ones in the unthinned subunit, in both cases irrespective of fire treatment, from 2002 to 2005 and from 2002 to 2012 were significant as were those concerning the 2005 to 2012 interval between a larger increase in the thinned and burned combination and a marginal one in the unthinned and unburned combination and between the former and a small decrease in the burned but unthinned combination. For live crown variables, ANOVA identified significant influences of the fire treatment × inventory year (p=0.0479) and thinning treatment × fire treatment × inventory year (p =0.0270) interactions on crown length along with a thinning × fire treatment effect (p=0.0440) on the change in length from 2002 to 2005 and a fire treatment effect (p=0.0373) on the change from 2002 to 2012. Initially, significant disparities were confined to unburned stand portions where crown length was less in the thinned than in the unthinned subunit, but at the final inventory the lone discrepancy occurred in the thinned subunit where it was less in the burned than in the unburned portion. Also disclosed as significant by the LSD test were differences in the change in length between an increase in the thinned but unburned combination and decreases in all other treatment combinations for both the 2002 to 2005 and the 2002 to 2012 periods. For live crown percentage, the inventory year (p<0.0001) plus the fire treatment × year (p=0.0049) and thinning treatment × fire treatment × year (p=0.0172) interactions proved to be significantly influential, while fire treatment affected the change in percentage from 2002 to 2005 (p=0.0282) and from 2002 to 2012 (p=0.0049) as did the thinning × fire treatment interaction concerning the former interval (p=0.0310). In mean comparisons, a lower percentage in the thinned and burned combination differed from higher ones in the three remaining treatment combinations at both the 2005 and 2012 inventories while a more negative change in percentage in the burned portion of the thinned subunit differed from

Inventory year and changes	Thinning and burning treatment	Height (m)	DBH (cm)	Live crown (m)	Live crown %	Basal area (m^2ha^{-1})	Total trees (stems ha^{-1})	Dead trees (stems ha^{-1})	Dead trees %
2002	Thinned/chipped								
	Burned	17.8ab	42.7ab	8.9ab	50.0a	50.6ab	361ab	15a	4.2a
	Unburned	17.5ab	38.6b	8.4b	48.4a	45.1ab	390a	15a	3.9a
	Unthinned								
	Burned	17.0b	43.1ab	9.3ab	55.4a	36.2b	247b	20a	8.1a
	Unburned	20.2a	51.8a	10.3a	53.2a	63.3a	307ab	20a	6.5a
2005	Thinned/chipped								
	Burned	21.1a	55.6a	6.9a	29.2b	28.1b	119c	40a	33.6a
	Unburned	21.3a	49.4a	10.0a	47.6a	30.1b	153bc	5a	3.3b
	Unthinned								
	Burned	16.9b	42.3a	8.0a	46.2a	34.1b	237ab	5a	2.1b
	Unburned	19.6ab	51.3a	8.6a	44.2a	65.7a	326a	20a	6.1b
2012	Thinned/chipped								
	Burned	22.4a	58.9a	7.1b	28.2b	28.6b	109c	40a	36.7a
	Unburned	22.2a	51.7ab	10.6a	47.6a	33.2b	158bc	5a	3.2b
	Unthinned								
	Burned	17.7b	42.1b	7.5ab	41.6a	31.4b	252ab	15a	5.9b
	Unburned	20.0ab	51.4ab	9.0ab	47.2a	70.0a	346a	15a	4.3b
2002 to 2005	Thinned/chipped								
	Burned	+3.3a	+12.9a	–2.0b	–20.8b	–22.5b	–242b	+25a	+29.4a
	Unburned	+3.8a	+10.8a	+1.6a	–0.8a	–15.0b	–237b	–10a	–0.6b
	Unthinned								
	Burned	–0.1b	–0.8b	–1.3b	–9.2ab	–2.1a	–10a	–15a	–6.0b
	Unburned	–0.6b	–0.5b	–1.7b	–9.0ab	+2.4a	+19a	0a	–0.4b
2005 to 2012	Thinned/chipped								
	Burned	+1.3a	+3.3a	+0.2a	–1.0a	+0.5a	–10b	0a	+3.1a
	Unburned	+0.9a	+2.3ab	+0.6a	0.0a	+3.1a	+5ab	0a	–0.1a
	Unthinned								
	Burned	+0.8a	–0.2b	–0.5a	–4.6a	–2.7a	+15ab	+10a	+3.8a
	Unburned	+0.4a	+0.1b	+0.4a	+3.0a	+4.3a	+20a	–5a	–1.8a
2002 to 2012	Thinned/chipped								
	Burned	+4.6a	+16.2a	–1.8b	–21.8b	–22.0c	–252b	+25a	+32.5a
	Unburned	+4.7a	+13.1a	+2.2a	–0.8a	–11.9bc	–232b	–10a	–0.7b
	Unthinned								
	Burned	+0.7b	–1.0b	–1.8b	–13.8ab	–4.8ab	+5a	–5a	–2.2b
	Unburned	–0.2b	–0.4b	–1.3b	–6.0ab	+6.7a	+39a	–5a	–2.2b

[1]Within each table component, means sharing a common letter do not differ significantly at α = 0.05 according to the LSD test; each mean is based on values from five plots (n = 5).
[2]Means preceded by "+" indicate increases while those preceded by "–" indicate reductions in mean values.

Table 1: Mensurational Characteristics and Their Changes in a Mixed Conifer Stand of the Lake Tahoe Basin as Influenced by Thinning, Chipping, and Underburning[1, 2]

a less negative one in its unburned counterpart for both the 2002 to 2005 and 2002 to 2012 periods.

Significant effects on basal area consisted of those of the thinning ($p=0.0491$) and fire ($p=0.0252$) treatments plus their interaction ($p=0.0285$) along with inventory year and the thinning treatment × inventory year interaction (both $p<0.0001$) according to ANOVA, while those on the change in this density measure were thinning treatment ($p<0.0001$) for the 2002 to 2005 period and both the thinning ($p=0.0009$) and fire ($p=0.0274$) treatments for the 2002 to 2012 period (Table 1). The LSD test indicated that at the initial inventory, the basal area was lower in the burned than the unburned portion of the unthinned subunit, but in the two subsequent inventories the prevailing distinction was one of a higher value in the unthinned and unburned treatment combination than in any of the other three combinations. Concerning the change in basal area from 2002 to 2005, a small decrease and a small increase in the burned and unburned portions, respectively, of the unthinned subunit diverged from large decreases in both portions of the thinned subunit, while from 2002 to 2012, an increase in the unthinned and unburned combination differed from large decreases in the two portions of the thinned subunit as did a smaller decrease in the burned but unthinned combination from the large one in the thinned and burned combination. For the other density measure used in the study, namely total tree count, ANOVA divulged that the inventory year and the thinning treatment × year interaction influenced the count itself (both $p<0.0001$) while the change in count was affected by thinning treatment for the 2002 to 2005 ($p<0.0001$), 2005 to 2012 ($p=0.0366$), and 2002 to 2012 ($p<0.0001$) periods. Following the initial inventory when the only significant disparity among treatments was a lower count in the burned but unthinned combination than in the thinned but unburned combination, a pattern extant at the remaining two inventories consisted of a higher value in the unthinned and unburned combination than in the thinned subunit irrespective of fire treatment plus a higher one in the burned but unthinned combination than in the thinned and burned combination. Significant disparities in the change in count entailed a small decrease and a small increase in the burned and unburned portions, respectively, of the unthinned treatment contrasted against large decreases in both portions of the thinned subunit for the 2002 to 2005 interval, a small increase in the unburned portion of the unthinned treatment contrasted against a small decrease in the thinned and burned combination for that of 2005 to 2012, and small increases in the two portions of the unthinned subunit contrasted against large decreases in either portion of the thinned treatment over the duration of the study. Of the tree mortality variables, ANOVA did not discern any significant effects regarding the standing dead count or its changes, but dead tree percentage was influenced by the thinning treatment × year (p=0.0263) and thinning × fire treatment × year (p=0.0226) interactions while the change in standing dead percentage was affected by the thinning treatment and the thinning × fire treatment interaction for the intervals encompassing 2002 to 2005 (p=0.0375 and p=0.0331, respectively) and 2002 to 2012 (both p=0.0409). Significant differences among treatments were also confined to the dead percentage, which was greater in the burned portion of the thinned subunit than in any other treatment combination at the 2005 and 2012 inventories, and to the change in dead percentage, for which a large increase in the thinned and burned combination contrasted against small decreases in all other treatments for the 2002 to 2005 and 2002 to 2012 intervals.

Stand volume

For stand volume variables, ANOVA identified the influences of the year of inventory (p=0.0048) and the thinning treatment × inventory year (p=0.0151) and fire treatment × inventory year (p=0.0486) interactions as significant on white fir board feet volume per acre, but there was no designation of significant differences among any of the means for this species and variable by the LSD test (Table 2). Somewhat similarly, ANOVA revealed that fire treatment (p=0.0441), inventory year (p=0.0151), and the thinning × fire treatment × year interaction (p=0.0416) influenced this volume measure regarding Jeffrey pine, and that the thinning treatment × year interaction did so for red fir (p=0.0307), but here again the LSD test disclosed no significant disparities among treatments at any inventory for either species. Statistical significance as derived from both ANOVA and the LSD test was lacking entirely concerning the board feet volume per acre of sugar pine. ANOVA did not disclose any significant influences regarding this measure for incense-cedar, but the LSD test deemed that its volume per acre was greater in the unburned than burned portions of the unthinned subunit at the 2002 inventory and again at that of 2005, which in part reflects that incense-cedar did not reside in the latter. Significant influences on cubic feet volume per acre of white fir consisted of those of inventory year (p=0.0002) plus the thinning treatment × year (p=0.0015) and fire treatment × year (p=0.0145) interactions, while for this volume measure in Jeffrey pine they consisted of fire treatment (p=0.0356) plus inventory year (p=0.0295), and in red fir the lone influence was the thinning treatment × year interaction (p=0.0323), but as was the case above concerning their board feet volumes, the LSD test did not detect distinctions among treatments at any of the inventories. In an additional similarity to the board feet measure, significant effects on cubic feet volume of sugar pine were entirely lacking as were significant disparities among treatments therein. However, in a departure from the above, ANOVA disclosed a significant influence on cubic feet volume of incense-cedar, specifically that of the thinning × fire treatment × inventory year interaction (p=0.0311), which was accompanied by disparities according to the LSD test that consisted of a higher volume in the unburned portion of the unthinned treatment than that in its burned counterpart or in the thinned but unburned combination, differences that persisted from the first through the last inventory. Because cubic meter volume was a direct transformation of cubic feet volume, the results detailed above for the latter also pertain to the former.

Regarding volume changes of individual species, that of board feet per acre in white fir was influenced by thinning treatment (p=0.0280) from 2002 to 2005 and by both the thinning (p=0.0122) and fire (p=0.0403) treatments from 2002 to 2012, with a single significant difference extant in the former interval, specifically that between an increase in the unthinned and unburned treatment and a substantial reduction in the thinned and burned combination, while increases in

Inventory year	Thinning and burning treatment	Board feet volume per acre					Cubic feet volume per acre					Cubic meter volume per hectare				
2002	Thinned/chipped	WF	JP	SP	IC	RF	WF	JP	SP	IC	RF	WF	JP	SP	IC	RF
	Burned	24280a	420a	8322a	2236ab	200a	5342.2a	81.4a	1611.5a	396.6ab	41.2a	373.56a	5.69a	112.69a	27.73ab	2.88a
	Unburned	17138a	7380a	4252a	146ab	1060a	3334.3a	1376.8a	847.6a	69.5b	230.0a	233.16a	96.28a	59.27a	4.86b	16.08a
	Unthinned															
	Burned	23890a	1700a	3884a	0b	0a	4780.2a	279.8a	810.2a	0.0b	0.0a	334.28a	19.57a	56.65a	0.00b	0.00a
	Unburned	30608a	6760a	6508a	6728a	400a	6138.6a	1046.4a	1169.6a	1310.3a	86.4a	429.26a	73.17a	81.79a	91.63a	6.04a
2005	Thinned/chipped															
	Burned	13222a	420a	8298a	2464ab	0a	2678.0a	81.4a	1584.8a	425.1ab	0.0a	187.27a	5.69a	110.82a	29.73ab	0.00a
	Unburned	13518a	6360a	4642a	60ab	340a	2502.5a	1173.4a	910.2a	27.4b	64.8a	175.00a	82.06a	63.65a	1.91b	4.53a
	Unthinned															
	Burned	21200a	1700a	4342a	0b	0a	4294.8a	279.8a	890.2a	0.0b	0.0a	300.33a	19.57a	62.25a	0.00b	0.00a
	Unburned	32384a	6540a	6584a	7144a	500a	6458.8a	1023.4a	1186.6a	1376.0a	99.2a	451.66a	71.57a	82.98a	96.22a	6.94a
2012	Thinned/chipped															
	Burned	12510a	460a	8346a	2708a	0a	2901.3a	92.2a	1547.1a	454.8ab	0.0a	202.88a	6.45a	108.19a	31.80ab	0.00a
	Unburned	15186a	7760a	4640a	80a	520a	2806.6a	1385.6a	910.2a	33.7b	100.2a	196.26a	96.89a	63.65a	2.36b	7.01a
	Unthinned															
	Burned	23938a	1920a	4506a	0a	0a	4827.8a	298.8a	925.9a	0.0b	0.0a	337.61a	20.89a	64.74a	0.00b	0.00a
	Unburned	35900a	6600a	6786a	7112a	620a	7124.2a	1036.2a	1235.2a	1382.4a	119.4a	498.19a	72.46a	86.38a	96.67a	8.35a

[1]Within each table component, means sharing a common letter do not differ significantly at α = 0.05 according to the LSD test; each mean is based on values from five plots (n=5)
[2]WF = White Fir, JP = Jeffrey Pine, SP = Sugar Pine, IC = Incense-cedar and RF = Red Fir.

Table 2: Volume by Species in a Mixed Conifer Stand of the Lake Tahoe Basin as Influenced by Thinning, Chipping, and Underburning[1,2].

Citation: Walker RF, Swim SL, Fecko RM, Johnson DW, Miller WW (2015) Long-Term Growth of Sierra Nevada Mixed Conifer in Response to Mechanized Thinning, Slash Mastication, and Prescribed Fire. Forest Res 4: 159. doi:10.4172/2168-9776.1000159

the unthinned subunit irrespective of fire treatment contrasted against a large reduction in the thinned and burned combination for the latter (Table 3). In Jeffrey pine, ANOVA revealed that the thinning (p=0.0430) and fire (p=0.0371) treatments plus their interaction (p=0.0109) affected the change in board feet volume, influences specific to the 2005 to 2012 period when a large increase in the unburned portion of the thinned subunit surpassed small increases in the three remaining treatment combinations. Neither significant effects nor significant differences were in evidence regarding changes in board footage for sugar pine and incense-cedar, but for red fir a thinning treatment influence (p=0.0422) for the 2002 to 2012 interval was accompanied by a distinction between an increase in the unthinned and unburned treatment and a decrease in the thinned but unburned combination. In cubic feet units, the change for white fir was affected by the thinning and fire treatments from 2002 to 2005 (p=0.0075 and p=0.0276, respectively) and 2002 to 2012 (p=0.0053 and p=0.0354, respectively), and in both cases the LSD test distinguished a substantial reduction in the burned portion of the thinned subunit from every value elsewhere. The change in cubic footage for Jeffrey pine paralleled that noted above regarding board feet, as the thinning and fire treatments plus their interaction (p=0.0345, p=0.0313, and p=0.0232, respectively) were influential from 2005 to 2012 as before while the LSD test again distinguished a large increase in the thinned but unburned combination from small ones everywhere else. However, sugar pine was the sole species for which both significant effects and significant disparities among treatments were absent regarding the change in cubic feet, as that in incense-cedar was affected by the thinning × fire treatment interaction during the 2002 to 2005 (p=0.0334) and 2002 to 2012 (p=0.0384) periods, while the thinning treatment influenced this change in red fir during the latter (p=0.0416). In each of these cases, an increase in the unburned portion of the unthinned subunit differed from a decrease in this portion of the thinned subunit according to the LSD test. As before, all statistical interpretation presented above concerning cubic feet volume also applies to that expressed as cubic meters.

When combined across species, board feet volume per acre was influenced by inventory year (p=0.0029) and the thinning treatment × year interaction (p=0.0091) according to ANOVA, while its change was affected by thinning treatment alone for the 2002 to 2005 (p=0.0183) and 2002 to 2012 (p=0.0135) intervals (Table 4). Only a single significant disparity between volumes was revealed by the LSD test, specifically that between a higher one in the unthinned and unburned treatment combination and a lower one in the thinned and burned combination at the 2012 inventory. As for the change, an increase in board footage in the unthinned and unburned treatment from 2002 to 2005 contrasted against a large decrease in the thinned and burned combination while increases in the unthinned subunit irrespective of fire treatment contrasted against the latter for the 2002 to 2012 interval. Combined cubic feet volume was affected by inventory year (p=0.0002) and both the thinning treatment × year (p=0.0007) and fire treatment × year (p=0.0453) interactions, while its change was influenced by thinning treatment from 2002 to 2005 and from the former to 2012 (both p=0.0044). At the 2005 and 2012 inventories, the LSD test distinguished a higher cubic footage in the unthinned and unburned combination than those in the thinned subunit regardless of fire treatment, and for changes in this measure, it distinguished a small reduction in the burned portion and an increase in the unburned portion of the unthinned treatment from a large decrease in the thinned and burned combination during the 2002 to 2005 period and increases in both portions of the unthinned treatment from the latter during the 2002 to 2012 period. Here again, statistical inferences about

Change	Thinning and burning treatment	Board feet volume per acre					Cubic feet volume per acre					Cubic meter volume per hectare				
2002 to 2005	Thinned/chipped															
		WF	JP	SP	IC	RF	WF	JP	SP	IC	RF	WF	JP	SP	IC	RF
	Burned	–11058b	0a	–24a	+228a	–200a	–2664.2b	0.0a	–26.7a	+28.5ab	–41.2a	–186.29b	0.00a	–1.87a	+2.00ab	–2.88a
	Unburned	–3620ab	–1020a	+390a	–86a	–720a	–831.8a	–203.4a	+62.6a	–42.1b	–165.2a	–58.16a	–14.22a	+4.38a	–2.95b	–11.55a
	Unthinned															
	Burned	–2690ab	0a	+458a	0a	0a	–485.4a	0.0a	+80.0a	0.0ab	0.0a	–33.95a	0.00a	+5.60a	0.00ab	0.00a
	Unburned	+1776a	–220a	+76a	+416a	+100a	+320.2a	–23.0a	+17.0a	+65.7a	+12.8a	+22.40a	–1.60a	+1.19a	+4.59a	+0.90a
2005 to 2012	Thinned/chipped															
	Burned	–712a	+40b	+48a	+244a	0a	+223.3a	+10.8b	–37.7a	+29.7a	0.0a	+15.61a	+0.76b	–2.63a	+2.07a	0.00a
	Unburned	+1668a	+1400a	–2a	+20a	+180a	+304.1a	+212.2a	0.0a	+6.3a	+35.4a	+21.26a	+14.83a	0.00a	+0.45a	+2.48a
	Unthinned															
	Burned	+2738a	+220b	+164a	0a	0a	+533.0a	+19.0b	+35.7a	0.0a	0.0a	+37.28a	+1.32b	+2.49a	0.00a	0.00a
	Unburned	+3516a	+60b	+202a	–32a	+120a	+665.4a	+12.8b	+48.6a	+6.4a	+20.2a	+46.53a	+0.89b	+3.40a	+0.45a	+1.41a
2002 to 2012	Thinned/chipped															
	Burned	–11770b	+40a	+24a	+472a	–200ab	–2440.9b	+10.8a	–64.4a	+58.2ab	–41.2ab	–170.68b	+0.76a	–4.50a	+4.07ab	–2.88ab
	Unburned	–1952ab	+380a	+388a	–66a	–540b	–527.7a	+8.8a	+62.6a	–35.8b	–129.8b	–36.90a	+0.61a	+4.38a	–2.50b	–9.07b
	Unthinned															
	Burned	+48a	+220a	+622a	0a	0ab	+47.6a	+19.0a	+115.7a	0.0ab	0.0ab	+3.33a	+1.32a	+8.09a	0.00ab	0.00ab
	Unburned	+5292a	–160a	+278a	+384a	+220a	+985.6a	–10.2a	+65.6a	+72.1a	+33.0a	+68.93a	–0.71a	+4.59a	+5.04a	+2.31a

[1]Within each table component, means sharing a common letter do not differ significantly at α = 0.05 according to the LSD test; each mean is based on values from five plots (n = 5)
[2]Means preceded by "+" indicate increases while those preceded by "–" indicate reductions in mean values
[3]WF = White Fir, JP = Jeffrey Pine, SP = Sugar Pine, IC = Incense-cedar and RF = Red Fir

Table 3: Changes in Volume by Species in a Mixed Conifer Stand of the Lake Tahoe Basin as Influenced by Thinning, Chipping, and Underburning[1,2,3]

Inventory year	Thinning and burning treatment	Board feet volume per acre	Cubic feet volume per acre	Cubic meter volume per hectare
2002	Thinned/chipped			
	Burned	35458a	7472.9a	522.55a
	Unburned	29976a	5858.2a	409.65a
	Unthinned			
	Burned	29474a	5870.2a	410.50a
	Unburned	51004a	9751.3a	681.89a
2005	Thinned/chipped			
	Burned	24404a	4769.3b	333.51b
	Unburned	24920a	4678.3b	327.15b
	Unthinned			
	Burned	27242a	5464.8ab	382.15ab
	Unburned	53152a	10144.0a	709.37a
2012	Thinned/chipped			
	Burned	24024b	4995.4b	349.32b
	Unburned	28186ab	5236.3b	366.17b
	Unthinned			
	Burned	30364ab	6052.5ab	423.24ab
	Unburned	57018a	10897.4a	762.05a
2002 to 2005	Thinned/chipped			
	Burned	–11054b	–2703.6b	–189.06b
	Unburned	–5056ab	–1180.0ab	–82.51ab
	Unthinned			
	Burned	–2232ab	–405.4a	–28.35a
	Unburned	+2148a	+392.7a	+27.46a
2005 to 2012	Thinned/chipped			
	Burned	–380a	+266.1a	+15.81a
	Unburned	+3266a	+558.1a	+39.02a
	Unthinned			
	Burned	+3122a	+587.7a	+41.09a
	Unburned	+3866a	+753.4a	+52.69a
2002 to 2012	Thinned/chipped			
	Burned	–11434b	–2477.5b	–173.25b
	Unburned	–1790ab	–621.9ab	–43.49ab
	Unthinned			
	Burned	+890a	+182.3a	+12.75a
	Unburned	+6014a	+1146.1a	+80.15a

[1]Within each table component, means sharing a common letter do not differ significantly at α = 0.05 according to the LSD test; each mean is based on values from five plots (n=5).
[2]Means preceded by "+" indicate increases while those preceded by "–" indicate reductions in mean values.

Table 4: Combined Volumes Across Species and Their Changes in a Mixed Conifer Stand of the Lake Tahoe Basin as Influenced by Thinning, Chipping, and Underburning[1,2].

cubic meter data are identical to those noted above for the cubic feet measure.

Relationships between variables

Generating 12 significant models in total, the crown development series of simple regressions was the smallest of the two series by a substantial margin (Table 5). Nevertheless, among the significant models therein, tree height and DBH at the initial inventory were related to live crown length at this inventory, height was again correlated with crown length at the final inventory, and live crown percent in 2005 was related to the 2002 live percentage. Furthermore, the board feet and cubic feet volumes per acre of white fir at the 2005 and 2012 inventories, plus the combined cubic feet volume at the latter, were all related to crown length in 2002. Every significant model in this series featured a positive correlation, while the variation in the dependent components explained by that in the independent variables fell within a range of 20% to 32%, inclusive. Significant models based upon cubic meter volume per hectare do not appear in Table 5 nor are they noted otherwise, but for the reason related on multiple occasions previously, every significant model herein incorporating the cubic feet volume measure is matched in every respect by one derived from the cubic meter measure.

The stand density series produced 110 significant models overall with 71 featuring basal area at the various inventories as the independent component while 39 relied upon total tree count for this purpose (Table 5). As for the former, when derived from the 2002 inventory it was paired in exclusively positive relationships with height at all three inventories, basal area in 2005 and 2012, and white fir, Jeffrey pine, incense-cedar, and combined board and cubic feet volumes in 2002 and 2005 plus all of these from 2012 except the Jeffrey pine cubic footage. Live crown percentage in 2002 was negatively related to the basal area at this inventory as well. Coupled with the 2005 basal area were the total tree counts of 2005 and 2012 along with the basal area at the latter inventory plus the white fir, incense-cedar, and combined board and cubic feet volumes of 2005 and 2012, all positive relationships. Based on the final inventory regarding both the independent and dependent variables, basal area was the former to which the tree count plus

Independent variables	Dependent variables	Correlation	Model F-test p-value	Model r^2
Crown development series:				
Live crown length, 2002	Height, 2002	Positive	.0092	.3211
Live crown length, 2002	DBH, 2002	Positive	.0271	.2434
Live crown length, 2002	White fir board feet volume per acre, 2005	Positive	.0166	.2793
Live crown length, 2002	White fir cubic feet volume per acre, 2005	Positive	.0164	.2803
Live crown length, 2002	White fir board feet volume per acre, 2012	Positive	.0150	.2868
Live crown length, 2002	White fir cubic feet volume per acre, 2012	Positive	.0141	.2908
Live crown length, 2002	Combined cubic feet volume per acre, 2012	Positive	.0428	.2089
Live crown length, 2012	Height, 2012	Positive	.0195	.2675
Live crown percent, 2002	Live crown percent, 2005	Positive	.0459	.2036
Stand density series:				
Basal area, 2002	Height, 2002	Positive	<.0001	.6390
Basal area, 2002	Live crown percent, 2002	Negative	.0377	.2186
Basal area, 2002	White fir board feet volume per acre, 2002	Positive	.0032	.3906
Basal area, 2002	Jeffrey pine board feet volume per acre, 2002	Positive	.0278	.2414
Basal area, 2002	Incense-cedar board feet volume per acre, 2002	Positive	.0114	.3064
Basal area, 2002	White fir cubic feet volume per acre, 2002	Positive	.0022	.4145
Basal area, 2002	Jeffrey pine cubic feet volume per acre, 2002	Positive	.0456	.2040
Basal area, 2002	Incense-cedar cubic feet volume per acre, 2002	Positive	.0088	.3242
Basal area, 2002	Combined board feet volume per acre, 2002	Positive	<.0001	.7747
Basal area, 2002	Combined cubic feet volume per acre, 2002	Positive	<.0001	.8514
Basal area, 2002	Height, 2005	Positive	.0187	.2708
Basal area, 2002	Basal area, 2005	Positive	<.0001	.6953
Basal area, 2002	White fir board feet volume per acre, 2005	Positive	.0070	.3395
Basal area, 2002	Jeffrey pine board feet volume per acre, 2005	Positive	.0251	.2490
Basal area, 2002	Incense-cedar board feet volume per acre, 2005	Positive	.0110	.3085
Basal area, 2002	White fir cubic feet volume per acre, 2005	Positive	.0080	.3308
Basal area, 2002	Jeffrey pine cubic feet volume per acre, 2005	Positive	.0374	.2190
Basal area, 2002	Incense-cedar cubic feet volume per acre, 2005	Positive	.0083	.3283
Basal area, 2002	Combined board feet volume per acre, 2005	Positive	<.0001	.6668
Basal area, 2002	Combined cubic feet volume per acre, 2005	Positive	<.0001	.6762
Basal area, 2002	Height, 2012	Positive	.0262	.2458
Basal area, 2002	Basal area, 2012	Positive	<.0001	.5942
Basal area, 2002	White fir board feet volume per acre, 2012	Positive	.0097	.3175
Basal area, 2002	Jeffrey pine board feet volume per acre, 2012	Positive	.0420	.2103
Basal area, 2002	Incense-cedar board feet volume per acre, 2012	Positive	.0123	.3007
Basal area, 2002	White fir cubic feet volume per acre, 2012	Positive	.0125	.2997
Basal area, 2002	Incense-cedar cubic feet volume per acre, 2012	Positive	.0088	.3239
Basal area, 2002	Combined board feet volume per acre, 2012	Positive	<.0001	.6508
Basal area, 2002	Combined cubic feet volume per acre, 2012	Positive	<.0001	.6476
Basal area, 2005	Tree count, 2005	Positive	.0023	.4126
Basal area, 2005	White fir board feet volume per acre, 2005	Positive	<.0001	.5788
Basal area, 2005	Incense-cedar board feet volume per acre, 2005	Positive	.0029	.3967
Basal area, 2005	White fir cubic feet volume per acre, 2005	Positive	<.0001	.6156
Basal area, 2005	Incense-cedar cubic feet volume per acre, 2005	Positive	.0018	.4262
Basal area, 2005	Combined board feet volume per acre, 2005	Positive	<.0001	.8442
Basal area, 2005	Combined cubic feet volume per acre, 2005	Positive	<.0001	.9096
Basal area, 2005	Basal area, 2012	Positive	<.0001	.9000
Basal area, 2005	Tree count, 2012	Positive	.0045	.3689
Basal area, 2005	White fir board feet volume per acre, 2012	Positive	<.0001	.5889
Basal area, 2005	Incense-cedar board feet volume per acre, 2012	Positive	.0037	.3818
Basal area, 2005	White fir cubic feet volume per acre, 2012	Positive	<.0001	.6027
Basal area, 2005	Incense-cedar cubic feet volume per acre, 2012	Positive	.0021	.4182
Basal area, 2005	Combined board feet volume per acre, 2012	Positive	<.0001	.8749
Basal area, 2005	Combined cubic feet volume per acre, 2012	Positive	<.0001	.9253
Basal area, 2012	Tree count, 2012	Positive	.0012	.4512
Basal area, 2012	White fir board feet volume per acre, 2012	Positive	.0022	.4146
Basal area, 2012	Incense-cedar board feet volume per acre, 2012	Positive	.0011	.4558
Basal area, 2012	White fir cubic feet volume per acre, 2012	Positive	.0013	.4439
Basal area, 2012	Incense-cedar cubic feet volume per acre, 2012	Positive	.0005	.5031

Basal area, 2012	Combined board feet volume per acre, 2012	Positive	<.0001	.6824
Basal area, 2012	Combined cubic feet volume per acre, 2012	Positive	<.0001	.7535
Tree count, 2002	Live crown length, 2002	Negative	.0450	.2051
Tree count, 2002	Live crown percent, 2002	Negative	.0164	.2800
Tree count, 2002	Red fir board feet volume per acre, 2002	Positive	.0142	.2904
Tree count, 2002	Red fir cubic feet volume per acre, 2002	Positive	.0138	.2925
Tree count, 2002	Red fir board feet volume per acre, 2005	Positive	.0298	.2363
Tree count, 2002	Red fir cubic feet volume per acre, 2005	Positive	.0315	.2321
Tree count, 2002	Red fir board feet volume per acre, 2012	Positive	.0227	.2564
Tree count, 2002	Red fir cubic feet volume per acre, 2012	Positive	.0227	.2564
Tree count, 2005	Basal area, 2005	Positive	.0023	.4126
Tree count, 2005	Red fir board feet volume per acre, 2005	Positive	.0196	.2673
Tree count, 2005	White fir cubic feet volume per acre, 2005	Positive	.0294	.2373
Tree count, 2005	Red fir cubic feet volume per acre, 2005	Positive	.0178	.2744
Tree count, 2005	Combined cubic feet volume per acre, 2005	Positive	.0387	.2166
Tree count, 2005	Basal area, 2012	Positive	.0008	.4754
Tree count, 2005	Tree count, 2012	Positive	<.0001	.9732
Tree count, 2005	White fir board feet volume per acre, 2012	Positive	.0409	.2124
Tree count, 2005	Red fir board feet volume per acre, 2012	Positive	.0335	.2274
Tree count, 2005	White fir cubic feet volume per acre, 2012	Positive	.0151	.2860
Tree count, 2005	Red fir cubic feet volume per acre, 2012	Positive	.0336	.2273
Tree count, 2005	Combined cubic feet volume per acre, 2012	Positive	.0188	.2703
Tree count, 2012	DBH, 2012	Negative	.0466	.2024
Tree count, 2012	Basal area, 2012	Positive	.0012	.4512
Tree count, 2012	White fir board feet volume per acre, 2012	Positive	.0360	.2220
Tree count, 2012	Red fir board feet volume per acre, 2012	Positive	.0316	.2318
Tree count, 2012	White fir cubic feet volume per acre, 2012	Positive	.0124	.3003
Tree count, 2012	Red fir cubic feet volume per acre, 2012	Positive	.0317	.2317
Tree count, 2012	Combined cubic feet volume per acre, 2012	Positive	.0294	.2371

[1]Models based on values from 20 plots (n=20).

Table 5: Significant Simple Linear Regression Models Relating Selected Mensurational Variables to Tree Crown and Forest Density Measures[1].

white fir, incense-cedar, and combined board and cubic feet volumes were again positively related. With total tree count serving as the independent component, and specifically that derived from the initial inventory, the dependent counterparts consisted of red fir board and cubic feet volumes for all three inventories in positive relationships along with live crown length and percentage in 2002 in negative ones. Paired with the total count of 2005 were basal area at this and the final inventories, the tree count at the latter, red fir board and cubic feet volumes in 2005 and 2012, white fir board feet volume in 2012 and its cubic footage in 2005 and 2012, and the combined cubic footage in 2005 and 2012, all positive correlations. The 2012 tree count was the independent counterpart to the 2012 basal area and white and red fir board and cubic feet volumes plus the final combined cubic footage in positive relationships and to the final tree DBH in a negative one. For the significant models in the stand density series overall, variation in the dependent components explained by that in their independent counterparts varied from 20% to 97%, inclusive. Consistently among the strongest of these models were ones involving combined volumes across species, which accounted for at least 65% of the variation therein when basal area served as the independent variable.

Discussion and Conclusions

Aside from the economic incentive of preemptively capturing merchantable wood fiber before it is lost to self-thinning, the rationale for thinning forest stands from an ecophysiological perspective is to reduce the competition for vital resources among the trees retained on the site. In western USA forests, this frequently revolves around water relations, and the capacity of reductions in stocking to reduce moisture stress has been documented in multiple species including Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) [27,28], lodgepole pine (*Pinus contorta* Dougl. ex. Loud.) [29], and Jeffrey pine [30,31]. From a mensurational standpoint, however, the objective in employing this practice is to enhance the growth of residual stems, and at its most basic the evidence indicating a successful outcome is the growth responses of individual stand constituents manifested in the changes that ensue in their dimensions. Over the decade encompassed by this study, the trees in the thinned stand subunit increased 4.4 m more in height and 15.4 cm more in DBH on average than those in the unthinned subunit. Unquestionably, these disparities reflect to some extent that there was an upper diameter limit imposed on the trees subject to harvest, although the influence of this factor was somewhat diminished by the fact that the limit was greater than the average tree size at the pretreatment inventory. Nevertheless, it is probable that they are also indicative of an enhanced post-treatment growth rate in thinned stand portions that was most apparent in the change in DBH from the 2005 to 2012 inventories, and it is this dimension that is generally considered to be the benchmark concerning thinning responses [32]. A likely contributor but of unknown magnitude to the enhanced growth of the trees in the thinned subunit was the chip layer created by the mastication and even redistribution of the logging slash over the site, which undoubtedly served to augment the mulching effect of the preexisting forest floor [33], a benefit that may have been rendered even more important by the paucity of precipitation relative to the requirements for the principal stand constituent, white fir, to flourish [5] and the subnormal precipitation deposited locally for much of the duration of the study. However, it is also probable that this was inconsequential in the growth responses of the burned portion of the thinned subunit, as much of the chip layer plus a substantial amount of the preexisting forest floor was consumed by the underburn [20]. The importance of crown size to tree growth was demonstrated here in regression models that linked both height and DBH at the pretreatment inventory to crown length therein and positively related tree height to crown length again at the final inventory, with the latter appearing to suggest that crown loss induced by the underburn diminished growth, but in fact there was no evidence in any of the changes in either height or DBH that the prescribed fire compromised the positive thinning response and this regression, among the weaker ones computed in the study, probably reflects in part crown loss that occurred in the unthinned treatment. Furthermore, another model indicated that the more live crown extant prior to treatment implementation the more the tree had afterward, and although a weak correlation prevailed in this case also, it lends little credence to an assumption that crown loss was of much influence in these growth responses. In point of fact, other models derived purely from initial inventory data indicated live crown percentage to be negatively related to basal area and crown length and percentage to be so related to total tree count, but the largest overall height, DBH, and basal area at the first inventory occurred within the portion to remain unburned of the unthinned subunit, suggesting that variation in crown development was not as of yet of overriding importance to tree growth on this site. Taken in total, the evidence suggests that because crown loss in the burned stand portions must be largely attributed to the underburn, it is likely that the preponderance of the loss was of older foliage in the lower crown that typically contributes little to the energy budget in conifers [34], or at least this was true in enough cases to negate any downward shift in the average dimensional growth response within the thinned subunit.

Given that volume growth at the stand level is a function of the growth of the individual trees therein and of the stocking level, that the intent of thinning operations is to reduce the latter, and that stand volume by any measure is usually correlated with stocking [35,36], it follows that the thinning implemented in this stand would reduce its volume. Using the 2005 inventory data to quantify the magnitude of the reduction when averaged across fire treatments, a 39% loss of the basal area in the thinned subunit, which approximates a thinning of moderate intensity according to conventional guidelines [32], was accompanied by a 25% reduction in board feet per acre and a 29% reduction in cubic feet per acre and cubic meters per hectare of combined volume across species. Expanding the time frame to encompass the entire study revealed only a marginal recovery in both stocking and volume, as the 2012 inventory indicated a 35% loss in basal area with 20% and 23% losses in the board feet and cubic volume measures, respectively, relative to that prevailing in the thinned subunit in 2002. Over the same span, basal area increased 4% while volume increased nearly 9% regardless of measure considered in the unthinned treatment. The linkage between stand volume and stocking level was further demonstrated here in a large assortment of strong regression models that positively related both board feet and cubic volumes across species to basal area, including ones that did so with the volume derived from a later inventory than the density value. In fact, every possible combination of volume and basal area within a given inventory and every possible pairing of a later volume with an earlier basal area were accounted for in these models, and in both cases every volume measure was as well. In part, these outcomes indicate that despite the higher dimensional growth rate of residual stems induced by the thinning, 10 years was not nearly sufficient for this factor to fully compensate for the concomitant diminished stocking. However, examination of the stem counts suggests that the basal area loss in the thinned subunit underrepresented the degree to which stocking was diminished, as they had decreased 64% at the 2005 inventory and 65% at that conducted in 2012. Apparent in the discrepancies between the two density measures was the influence of the upper diameter limit imposed by the thinning protocol, which effectively dictated that harvested trees be predominantly of larger pole and smaller young saw timber sizes which is the developmental stage during which tree growth and volume accrual often accelerate appreciably in western USA conifer forests [37]. Comparatively, stem counts in the unthinned subunit had increased 3% as of the 2005 inventory and 8% as of that in 2012 on average, reflecting some ingrowth into the stem size required for inclusion in the inventories. Nevertheless, total tree counts did not prove to have nearly the predictive value of basal area regarding stand volume, as significant regression models relating volume to the number of standing stems were few in number, disclosed weak correlations, and involved cubic volume measures only. An additional restriction on the overall volume growth within the thinned subunit related to the tree counts revealed at both post-treatment inventories was the mortality extant among standing stems in its burned portion, as approximately one-third were dead in 2005 with the proportion increasing somewhat as of 2012, and at each instance the percentage of standing dead therein exceeded those in all other treatment combinations by a large margin. Given the lack of any semblance of a parallel response in the unthinned treatment, this infers that mortality induced by the underburn resulted primarily from heightened injury associated with the combustion of the chip layer derived from the mastication process, and furthermore, given the aforementioned conclusion regarding the influence of crown loss on dimensional growth, it suggests that basal injury incurred from prolonged combustion of this layer, or more specifically irreparable damage to the vascular functioning of the lower bole, often proved to be lethal. The seeming incongruity between the outcome regarding dimensional growth, i.e. that the burn was of little consequence, and that here which clearly indicates that it killed a substantial number of trees either immediately or in an aftermath that extended over multiple years, may be explained by the assumption that larger residual stems in the thinned subunit accounted for most of the increase in tree dimensions therein noted previously while small ones frequently succumbed to the thermal injury inflicted in its burned portion. That smaller stems are particularly susceptible to bole damage is based on the fact that the insulating capacity of bark is essentially the only thermal protection afforded the phloem and cambial layers in tree boles subjected to fire, and that its effectiveness is largely a reflection of its depth which in turn reflects tree age and stem diameter among other factors [38]. Additionally, and perhaps of particular pertinence here due to the protracted combustion resulting from the surface fuel additions manifested in the chip layer, strong linkages have been established between bark thickness and the exposure time required to reach lethal cambial temperatures for several western USA conifers [39]. Nevertheless, the finding here that the thinned and burned treatment combination incurred the largest overall volume loss reflects in part that standing dead trees, although a component of extant volume in this stand portion, did not contribute to its accrual thereafter, which in essence decrees that this outcome conforms to that of other trials conducted in the western USA, perhaps most prominently ones involving ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) stands where diminished cubic volume growth ensued when prescribed fire was implemented following thinning operations [40,41,42].

Examination of the contributions of the individual constituent species to the overall volume growth responses to treatment of the subject stand revealed some variability among them. With white fir constituting the dominant species to such extent that it accounted for nearly three-quarters of the composition, it is apparent that its responses would largely parallel those overall as denoted previously, and such was the case with a pronounced reduction in volume associated with the thinning that was far more apparent when underburning followed it. However, with a 35% reduction in board feet per acre and a 40% reduction in cubic feet per acre and cubic meters per hectare on average from 2002 to 2005 along with one of 33% for the former and of 34% for the latter two measures from 2002 to 2012, losses specific to this fir exceeded those incurred for all species combined. In comparison, an approximate 10% volume increase prevailed in the unthinned subunit from the first to last inventory. It is probable that three factors contributed to the disparity between the white fir responses and those across species, with the first and most immediate being the targeting of this species in the thinning operation, which was reflected to some extent in an array of regression models of varying strength that expressed positive relationships between its volume and basal area within each inventory and in all possible pairings of a later volume with an earlier basal area and with inclusion of each of the three volume measures in all cases. Another group of models, although less extensive and with somewhat weaker correlations overall, revealed such linkages between white fir volume and total tree count. Second, the afore mentioned marginal adaptation of white fir to the site, as is made apparent when the Laacke [5] treatise is consulted, likely resulted in a muted response upon its release via thinning. Third, and most pertinent where the extreme losses associated with burned portion of the thinned subunit are concerned, the survivability of this fir when subjected to even the moderate risk imparted by a low intensity ground fire is questionable up until it reaches an advanced age [14], with one of its traits, that of delayed self-pruning, perhaps reflected in regression models that positively related its volume, with all measures represented, at both posttreatment inventories to live crown length at the outset of the study, suggesting that trees with larger crowns initially could better afford crown damage caused by the underburn. Another white fir trait, specifically its propensity toward slow development of thick bark plates, undoubtedly rendered the prolonged combustion caused by the addition of the chip layer particularly hazardous. Jeffrey pine, the second most prevalent stand constituent, was the only species to exhibit statistical distinctions among the various treatment combinations during the 2005 to 2012 interval that were manifested in larger volume increases in the unburned portion of the thinned subunit than in any other stand portion. These increases amounted to one of 22% in the board feet measure and 18% for each of the cubic volume measures. It can be reasonably assumed that Jeffrey pine is well adapted to this site [6], perhaps more so than any of the other species, and that its shade intolerance probably accounts for its positive volume response to the thinning, but supplementary support for the latter assumption from the regression analysis was somewhat oblique in that significant models encompassing Jeffrey pine volume at every one of the inventories related it to basal area, but in each of these it was the basal area present at the initial inventory and the correlations, in addition to being weak, were exclusively positive, so in effect these models may largely infer that the more pretreatment competition this species endured the greater the post-treatment release. Another noteworthy aspect of the Jeffrey pine response here is that although it is considered to be highly resistant to fire injury [3, 11, 12], this attribute was not in evidence given that the release apparent in the thinned subunit did not extend to its burned portion, which suggests that the combustion of the chip layer posed a hazard even to this species. Another eastern Sierran study in which Jeffrey pine in a pure stand responded favorably to thinning using the cut-to-length system but without subsequent mastication of the resultant slash mats also revealed that the response was essentially negated if underburning accompanied the thinning [43]. Approximately equal in representation to that of Jeffrey pine was sugar pine, a species unique in this study in that no statistical significance was detected regarding any variable in its responses to treatment or in any of the related disparities among treatments, and furthermore, the regression analysis did not divulge any significant models pertaining to it. Consequently, it can only be concluded that the treatments imposed herein were inconsequential to this species during the interval between the initial and final inventories. Incense-cedar and red fir, the two species with the most meager representation in the stand, also had in common that they were both absent entirely in one of the treatment combinations, specifically the unthinned but burned one, throughout the study. Nevertheless, incense-cedar displayed a distinctly positive volume growth response in the unthinned and unburned combination that, although confined to the cubic volume measures, amounted to an approximate 5% increase for both the 2002 to 2005 and 2002 to 2012 intervals. Classified as intermediate in shade tolerance [2], this outcome suggests that there is sufficient flexibility in its need for sunlight to grow relatively well despite substantial between-tree competition, and a large group of significant regressions attested to this conclusion by relating higher incense-cedar volume to higher basal area, and although of varying strength, all volume measures were represented as were all within-inventory as well as pertinent cross-inventory pairings. Little can be discerned about the influence that fire may have imposed on the positive response in the unthinned subunit since incense-cedar did not reside in its burned portion, so the only inference that can be derived from the results here is that this species seemingly prospered where disturbance was least pronounced. Red fir was not only absent from the burned portion of the unthinned treatment for the entirety of the study, it was also absent from the burned portion of the thinned subunit in 2005 and 2012, and while significant volume growth responses for this species were extant only for the 2002 to 2012 interval, they encompassed both the board feet and cubic volume measures. Here again, the unthinned and unburned treatment combination was of note, in this case because it produced the only volume increases for this species amounting to 55% and 38% gains in board feet and the cubic measures, respectively. Also significant were the same array of regression models noted above for incense-cedar, but in addition to being specific to red fir, those here featured total tree count as the density measure instead of basal area. Regardless, to the extent that an inference can be drawn from these results, they reflect the adaptability of this species to heavy shade [2] and indicate that it also prospered in the absence of disturbance.

In summary, combined effects of thinning using cut-to-length harvesting with mastication and dispersal of the resulting slash mats along with subsequent underburning on individual tree and stand level growth measures were quantified in an eastern Sierra Nevada mixed conifer stand with a heavy representation of white fir. One decade after treatment, trees in the stand subunit subjected to thinning exhibited substantial gains in height and DBH when compared to the unthinned treatment, with the increases attributable to the thinning protocol employed and to enhanced growth of residual stems, while the prescribed underburn was largely inconsequential in these responses. However, at the stand level, diminished board feet and cubic volumes prevailed in the thinned subunit through the end of the study, most especially in its burned portion, which reflected a reduction in stocking exacerbated by further loss induced by the underburn. Volume losses by white fir alone in the thinned and burned stand portion essentially accounted for the total incurred therein. Jeffrey pine was the only species among stand constituents to demonstrate a positive volume growth response to thinning, but the gain was negated if it was followed by underburning. Among the remaining resident species, treatment influences were inconsequential regarding sugar pine, while volume growth of incense-cedar and red fir, which were exceedingly minor stand constituents, was enhanced where neither thinning nor burning were implemented. The silvicultural practices investigated here are viewed as restoration treatments particularly appropriate for sensitive sites in western USA forests, and these results provide land managers insight into their influences on stand growth in a prominent eastern Sierran forest cover type.

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