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Alternative approaches to mixed conifer forest restoration: partitioning the competitive neighborhood

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Abstract Forest restoration efforts in the intermountain west of North America generally seek to promote the continuation of pine dominance, enhance wildlife habitat, and decrease hazardous fuels, thereby mitigating catastrophic losses from various stressors and disturbances. We propose a method of focal tree release thinning that partitions the competitive neighborhood to provide alternative approaches to managers. Specifically, we sought to examine how competition index (CI) derived harvest simulations alter forest structure, composition, and variability, and evaluate the ecological implications and efficacy of achieving management recommendations. We used a tree inventory collected across 38 experimental plots in the mixed conifer forest of the Sierra Nevada and simulated post-harvest structure using common silvicultural prescriptions to the ownership and cover type. We calculated competition values for all trees using 10 CIs and simulated harvests from two defined integrals of each corresponding probability density function to compare with the standard marking scenario, for a total of 21 harvest simulations. We assessed post-harvest structure through tree density and diameter distributions, basal area by species, and a structural diversity index. Post-harvest conditions exhibited differences in levels of structural diversity and species dominance; however we did not detect any influence on tree density across diameter classes. Most simulations resulted in a decline of non-pine species basal area relative to the default, while only 3 thinning scenarios showed concomitant increases in pine. Every simulation resulted in greater variance of structural diversity than the default marking guidelines. Review of this method highlighted the variability in tree ranked competitive status across indices. We emphasize that no harvest simulation by CI was clearly superior in all aspects of achieving desired objectives, and there was no clear benefit to incorporating inter-tree distances to calculate CI. We

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consistently observed favorable outcomes in harvest simulations derived from an open-grown crown width parameter which averts the need for tree distance measurements. This approach can be tailored across multiple individual plots, each maintaining unique competitive environments that reflect local tree neighborhoods.

Keywords Competition · Restoration · Sierran mixed conifer · Thinning · Structural diversity

Introduction

Silvicultural practices in mixed conifer forests of the Sierra Nevada in California have increased emphasis on restoration treatments to decrease hazardous fuels, provide wildlife habitat and balanced growing stock, and increase resilience to biotic and abiotic disturbances and future climatic stressors (Nuniz-Mir et al. 2015). These efforts are often in response to decades of wildfire suppression and lack of density management, which has resulted in higher stocking levels of fire sensitive, shade tolerant species that has altered disturbance regimes and associated successional trajectories compared with historical reference conditions (Hessburg et al. 2007; Lydersen et al. 2013). Stand density management through thinning can decrease hazardous fuels (Agee and Skinner 2005), reduce mortality (Zhang et al. 2013), alleviate water stress (Aussenac and Granier 1988), and enhance residual tree growth (Daniel et al. 1979). While these practices are often assumed to increase and maintain complex structural heterogeneity within the stand (Contreras et al. 2011), traditional thinning approaches and targets may not explicitly achieve these goals (North et al. 2007). Heterogeneity and diversity of stand structure is characterized by variability in the horizontal and vertical distribution of foliage and biomass among species (Goff and Zedler 1968; Smith et al. 1997). Forests with high structural heterogeneity have been shown to support higher biodiversity either directly through the facilitation of the presence of a variety of tree, shrub and herbaceous species (Barbier et al. 2008), or indirectly through increasing variability in edaphic conditions and microsites which in turn influence the microbiota and faunal communities (McElhinny et al. 2005; Tews et al. 2003). Further, stands with high heterogeneity have been suggested to be resilient to intense disturbance events (Elmqvist et al. 2003; Thompson et al. 2009). Therefore, complexity and greater adaptive capacity through restoration may be equally as important as economically driven prescriptions aimed at increased basal area increment of designated crop trees on some land ownerships (Newton and Cantarello 2015; Stanturf 2015).

Management recommendations specific to mixed conifer restoration have been developed for public forestlands, and highlight the importance of patch size variance, retention of species, genetic and phenotypic diversity, and a revised diameter distribution to encourage pine dominance and create a multi-aged structure (North et al. 2009). In practice, foresters commonly use marking guidelines for tree removal constrained to specific diameter limits in order to decrease competitive stress to residual crop trees and simultaneously achieve ecological goals. While fundamentally sound, these practices may fail to address some objectives including achieving tree removal targets (O'Hara et al. 2012) for successful recruitment and up growth of shade intolerant species (Kenefic et al. 2005; North et al. 2007), fuel reduction (Agee and Skinner 2005), and greater structural variance. An evaluation of the efficacy of these treatments compared with novel approaches is critical to effectively meeting multiple and often compounding objectives (Jacobs et al. 2015), and marking guidelines established within a plant competition framework may offer a viable alternative to standard practices. Therefore, the continued assessment of restoration practices and their application warrants assessment given evolving demands on forestlands.

Plant competition is characterized by the interactions and dynamics by individuals within a community brought on by demand for a shared limiting resource which ultimately results in a hierarchical structure of stand demographics and resource allocation (Weiner and Thomas 1986; Burton 1993; Burkhart and Tomé 2012), that varies by species mixtures and phase of stand development. The subject of competition influence on growth and yield within forest stands has received extensive review and original work evaluated the predictive capability of competition on basal area increment (BAI) with a neighborhood competition index (Krajicek et al. 1961; Opie 1968; Bella 1971; Lorimer 1983; Martin and Ek 1984; Pretzsch et al. 2002; Stage and Ledermann 2008; Ledermann 2010). Competition indices are generally categorized as distance independent (DI), distance dependent (DD), and a relatively new semi-distance independent (SDI) (Stage and Ledermann 2008; Ledermann 2010). DI indices are derived from spatially independent tree and plot metrics based on ratios of stem dimensions and number of individuals within a plot, while the DD category extends this method to weight the competitor by its relative distance to the focal tree of interest. The SDI uses a DI approach but constrains the set of competitors to the inventory plot area. Competition indices were further adapted for use in vegetation control in plantation establishment to favor the survival and development of crop trees (Brand 1986; Morris and MacDonald 1991; Becagli et al. 2013; Coble 2013).

The utilization of competition indices (CI) in restoration efforts has received considerably less attention, yet may be useful due to their focal tree and gap oriented framework, particularly to the release of large, old trees in forest restoration efforts. These methods utilize a tree neighborhood level metric in contrast to standard marking guidelines applied at the stand scale. The competition value of any particular stem varies by setting and origination of the particular index. Therefore, our interest in this study is the assessment of marking guidelines based on CIs that use a tree neighborhood orientation in restoration efforts. This work is not intended as an extensive overview of CIs or their accuracy in predicting residual tree growth through BAI, but instead as an examination of applicable alternatives that may balance allocation of growing space within local tree neighborhoods and provide additional options to forest resource managers.

Materials and methods

Study area and sampling design

Field measurements were conducted in the Lassen National Forest in Plumas County, California (40.19°N, 121.31°W). The area ranges from 1500 to 1550 m in elevation, and features a Mediterranean climate characterized by hot, dry summers and cool, wet winters. Mean annual daily temperatures range from 1.4 to 18.6 °C in the winter and summer seasons, respectively, with mean annual precipitation of 102 cm falling mainly as snow (National Climate Data Center 2016). Soil types are a mix of Ultic and Vitrandic Haploxeralfs and the area is classified as a second growth mixed conifer cover type (SAF type 243; Eyre 1980), primarily composed of sugar pine (*Pinus lambertiana* Dougl.), ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.), white fir (*Abies concolor* Lindl. ex Hildebr.), and incense cedar (*Calocedrus decurrens* Torr.), that established after extensive logging during the early twentieth century. Low intensity, high frequency fires characterized the historical disturbance regime, and suppression of wildfires over the last few decades has increased tree density, notably fir and cedar, relative to past levels.

Sample plots were established around a total of 38 individual large (>63.5 cm) pine trees (ponderosa pine or sugar pine) in the summers of 2014–2015 that were designated for retention in an upcoming restoration thinning project. Within each 260 m^2 circular plot, all trees greater than 20.3 cm at dbh (diameter at breast height, 1.37 m) were identified by species and dbh was measured. All focal trees and a subsample of at least 3 competitor trees within each plot were measured for total height (m), height to live crown (m), and crown width (m). Stem maps of each plot were created by measuring the total distance and azimuth from the focal tree to each competitor. Stand density of these plots ranged from 128 to 560 trees ha^{-1} with a mean of 295 trees ha^{-1} while basal area ranged from 18.3 to 115.9 $m^2\ ha^{-1}$ with a mean of 58.3 $m^2\ ha^{-1}$, with the larger diameter classes dominated by sugar pine and ponderosa pine (Fig. 1).

Competition indices

We used inventory data to calculate CI values within each plot at the individual tree level. To fulfill our goals, we selected indices that were (1) most widely cited in the literature; (2) included as the default setting in primary forest growth and yield simulation systems, and; (3) developed in similar regions or forest types as those reported here. We calculated competition values at the tree level across a total of 10 indices; 3 distance independent (DI, C1-3); 1 semi-distance independent (SDI, C4), and 6 distant dependent (DD, C5-10) (Table 1). We included only one of the five developed SDI indices developed by Stage and Ledermann (2008) and Ledermann (2010) as all calculate competition as a function of area overlap between the subject tree and competitor which result in duplication of bimodal probability density functions and subsequent definition of trees identified for simulated harvest in this study.

The distance independent (DI) CIs do not require spatially explicit locations of competing trees and are common in tree and stand growth in forest simulation models as well as predictors of individual tree vigor. Krajicek et al. (1961) defined the CI as the proportion of individual, open grown tree crown area to the plot size which has been integrated as the default predictive variable in primary growth and yield software (Arney 2015; Keyser

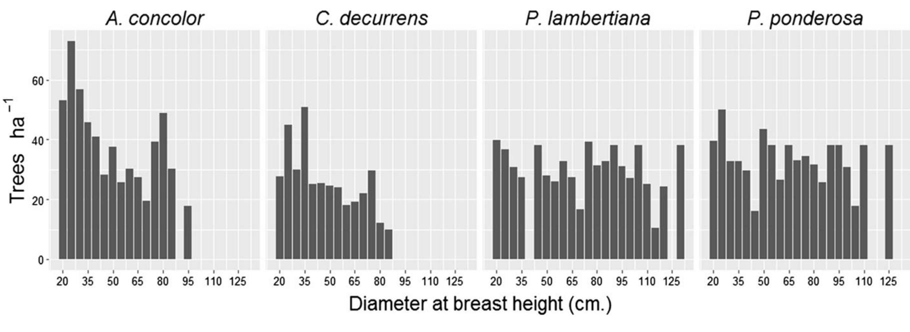

Fig. 1 Stem density of species by diameter class (5 cm. bin width) across all plots of pre-harvest simulation conditions used in this study

Table 1 Competition indices and associated equations and references used in analysis

Index No.	Catgegory	Source	Equation	Index identifier
C1	DI	Krajicek et al. (1961)	$\Sigma_{i=1}^{n}((\pi * CWO_i^2)/4)/S$	KR
C2	DI	Brand (1986)	$[\Sigma_{i=1}^{n} h_i * c_i/n]/h_j$	BR
C3	DI	Glover and Hool (1979)	$d_i/\check{D}$	GH
C4	SDI	Ledermann (2010)	$CWO_i^2(\pi/400)Nrep_i + \Sigma_{i=1}^{n} CWO_i^2 (\pi/400)Nrep_i(a_{ij}/a_j)$	LD
C5	DD	Biging and Dobbertin (1992)	$\Sigma_{i=1}^{n} CC_i/CC_j)(Dist_{ij} + 1)$	BD
C6	DD	Martin and Ek (1984)	$\Sigma\ D_i/D_j * e^{-(16 dist_{ij}/Dj - Di)}$	ME
C7	DD	Bella (1971)	$\Sigma_{i=1}^{n}(O_i * D_i)/(Z * D_j)$	BE
C8	DD	Hegyi (1974)	$\Sigma_{i=1}^{n} D_i/D_j * Dist_{ij})$	HE
C9	DD	Lorimer (1983)	$(D_i/D_j)/Dist_{ij}$	LO
C10	DD	Canham et al. (2004)	$\Sigma_{i=1}^{s}\Sigma_{i=1}^{n}\lambda_i(D_i)^{\alpha}/(Dist_{ij})^{\beta}$	CA

Where CWO is open growth crown width (m); *S* is sample plot size; h_i and h_j correspond to focal and competitor tree height, respectively; D_i and D_j correspond to the diameter at breast height of the focal and competitor tree, respectively; Nrep is the number of individuals on the plot; CC is the crown cross sectional area at a given percentage of focal tree height; D bar is the arithmetic mean diameter of the plot; O_i is the area of the zone of overlap between the competitor tree and the focal tree; *Z* is the crown area of the focal tree; $Dist_{ij}$ is the distance between the inter-tree distance between the focal and competitor trees; α estimates how the crowding scales with the size of the competing trees; β estimates the effect of distance on the competitor tree, and λ is a multiplier to adjust the CI for inter-intra species specific competition

2015). Brand (1986) uses a model to predict tree vigor by using competitor height to account for light availability in relation to the focal tree, and Glover and Hool (1979) use a simple ratio of the competitor tree dbh to the plot level dbh arithmetic mean. Stage and Ledermann (2008) and Ledermann (2010) derived a CI that is limited to defining competitors by the plot size and overlap of tree dimensions yet remains spatially independent. We selected the Crown Competitor Factor index (Ledermann 2010) as it represents relative growing space of each tree within the plot and is similar in concept to Krajicek et al. (1961). We used regression equations derived from the Inland California and Southern Cascades (CA) variant of the Forest Vegetation Simulator (FVS) (Keyser 2015) to estimate open grown crown area for the Krajicek et al. (1961) and Ledermann (2010) indices.

Indices using spatially explicit stem maps are underrepresented in application compared to the DI category owing to localized site and species interactions as well as the required intensive measurements to create stem maps. Hegyi (1974) proposed an index that is determined by a size ratio relationship between the competitor and focal tree weighted by the distance, assuming that competition status is determined by size difference and proximity between the two stems (Tomé and Burkhart 1989; Contreras et al. 2011). Hegyi's index (1974) was modified slightly by Biging and Dobbertin (1992) to reflect crown cross-sectional area instead of diameter at a given percentage of the focal tree height.

Lorimer (1983) and Martin and Ek (1984) integrated the inter-tree distance from the focal to competitor tree index developed by Glover and Hool (1979), weighting distance as an inverse and exponential relationship, respectively. Bella's (1971) index that uses the area overlap zones between the crown of the focal tree and competitor, which assumes that growing space is a function of tree dimension and therefore that competition status increases with area overlap. Canham et al. (2004) refined this with a crowding index that assigns competition value as a function of size and distance of neighboring trees and adjusts this index to weight inter-intra species specific competition with an adjustment factor. The plot size of 9.1 m in radius used in our study aligns with current operational silvicultural practices used in gap manipulation and focal tree release marking guidelines, and follows Lorimer's (1983) recommendation of defining the local neighborhood as a minimum of 3.5 times the mean crown radius.

Harvest simulations

We sought to compare residual stand structure following a standard thinning operation currently used by the U.S. Forest Service to simulations based on user-defined quantiles of the probability density function of each calculated CI. The prescription written by a U.S. Forest Service silviculturist used a hybrid of single tree and group selection thinning regime across the stand matrix coupled with a focal tree release treatment around large diameter, legacy sugar pine and ponderosa pine, in accordance with mixed conifer restoration methods proposed by North et al. (2009), Knapp et al. (2012), and O'Hara et al. (2012). For the scope of this work, we were specifically interested in the focal tree radial release component of the treatment, which is centered around large pine stems >60.7 cm. dbh and removes all trees between 25.4 and 60.7 cm. dbh within a 9.1 m radius while retaining all pine >60.7 cm. and white fir and incense cedar >76 cm. dbh (Table 2). We used this approach as a baseline to compare two simulated scenarios of tree removal from the probability density function of each CI, specifically the removal of trees in: (1) the upper 66th percentile and (2) the mid-66th percentile (17th–83rd percentile) of each CI. Scenario 1 is intended to release the residual focal tree for enhanced basal area increment while retaining less competitive trees to enhance structure. Scenario 2 is meant to emphasize structural diversity through maintaining tree clumping (high competition) patterns that are indicative of old-growth conditions of this forest type (Lydersen et al. 2013), by retaining those trees with the highest and lowest levels of competition (Table 2). Thus, both practices aim to simultaneously encourage tree and stand growth while promoting structural variance, however the relative emphasis of these goals varies by scenario.

Statistical analyses

All tests and analyses were conducted in the R software Environment (Version 3.3.1) (R Development Core Team 2016). We used the *lme4* package (Bates et al. 2016) to assess

Table 2 Harvest simulations used in this study

Harvest simulation	Description
1	Remove all trees greater than the 33rd percentile of the CI value probability density function, regardless of species
2	Remove all trees within the 17th to 83rd percentile of the CI value probability density function, regardless of species
Default	Radial release around select healthy sugar and ponderosa pine > 61 cm. dbh to a distance of 9.1 m. All trees > 76.2 cm dbh and all healthy pine > 40.6 cm. dbh will be retained to maintain existing clumps within radial release

post-harvest stem density across diameter classes. Tree density was log transformed to stabilize variance. Diameter class and simulation were designated as fixed effects with the addition of a random effect to account for the hierarchical nature of the data, and we used the *boot* package (Canty and Ripley 2016) to estimate confidence intervals. We tested differences in tree diameter distributions using a Kolmogorov–Smirnov test with a Bonferroni correction to adjust for multiple comparisons ($\alpha = 0.1$).

Mean residual basal area was compared for all species and across all competition indices and harvest simulations and compared within a mixed effects analysis of variance (ANOVA) similar to the approach used for tree density previously described. Pre-harvest and residual diameter distributions were plotted with *ggplot2* package (Wickham and Chang 2015). Shannon's post hoc diversity index (PDI) (Staudhammer and LeMay 2001) was calculated to assess relative changes in forest structure among harvest simulations, defined as

$$H' = \sum_{i=1}^{S} pi \ \ln \ pi \tag{1}$$

where pi is the proportion of individuals in the ith species, and S is the number of species. This calculation was then repeated for basal area by dbh class and height, and then averaged to scale the index (Staudhammer and LeMay 2001). We used the *violplot* package (Adler 2015) to simultaneously represent kernel density estimates and quantiles across all plots under each thinning simulation.

Results

Tests failed to detect a strong difference in any of the tested harvest simulations on the coefficients of tree density in comparison to the default marking guides (Fig. 2a–d), despite some general trends in the DD category. There were no differences in diameter distributions among the CI harvest simulations, nor were there any differences from the default marking scenario given the results of the Kolmogorov–Smirnov tests ($p > 0.88$; Fig. 3). The default, BR.2, GH.2, HE.2, and LO.2 simulations showed a complete removal of trees in the 30-55 dbh range in comparison to other groups, reducing the amount of trees available for up growth to the larger diameter classes. Most simulations resulted in a fairly even distribution of trees throughout the range of diameter classes, with the exception BR.1 and GH.1 which slightly resemble a reverse-J shape (Fig. 3).

While there were no differences in diameter distribution in any of the tested harvest simulations, we did observe significant patterns in residual basal area (m^2 ha^{-1}) that varied by species (Fig. 4). White fir and incense cedar basal area was consistently lower than the default across the majority of simulations, with the exception of the BD and ME.2, which exhibited higher basal area and no difference, respectively, from the default scenario. Similarly, incense cedar was higher in the BD and ME simulations. The LO.2, KR.2, and HE.2 simulations resulted in notably higher values of ponderosa pine than the default, while the ME.2, BR.2, and both BD categories exhibited no difference. Finally, there was higher residual basal area of sugar pine in most of the simulations with the exception of the LD.1-2, CA.1-2, BE.1-2, GH.1 and BR.1 categories, which resulted in no difference from the default marking scenario.

PDI exhibited high variance across all simulations, especially when compared with the default marking guides (Fig. 5). The simulations with the BE index had the highest PDI values, followed by the LD groups, which were significantly higher than the default. The

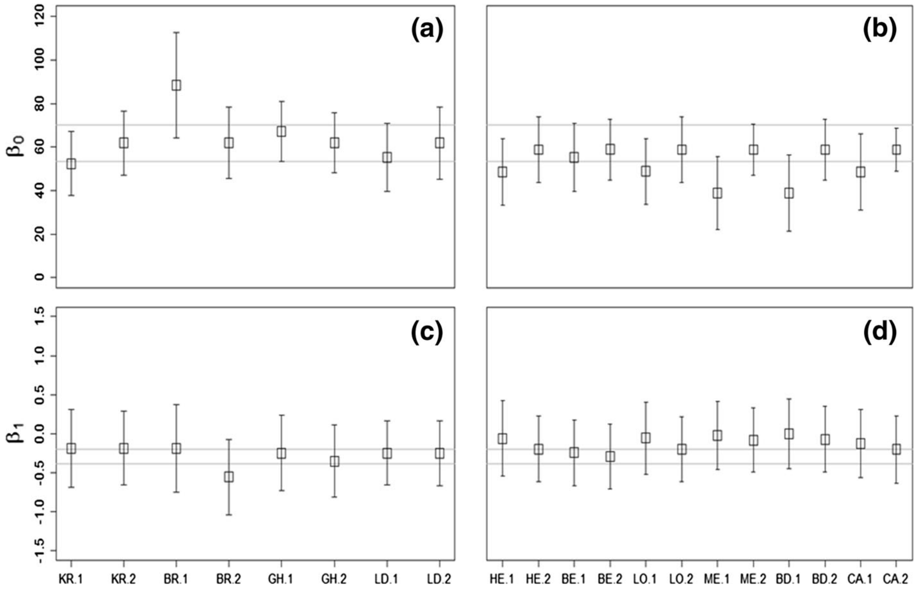

Fig. 2 Regression intercepts (β_0) (**a**, **b**), and slopes (β_1) (**c**, **d**) of trees per hectare by diameter class bootstrapped coefficients. *Panel columns* correspond to the distance independent, dependent and semi-independent competition index category by harvest simulations, respectively. *Boxes* represent model coefficients; *error bars* represent 95% confidence intervals. *Horizontal gray lines* illustrate the 95% confidence interval band for the default coefficients

KR.1-2, LO.2, BE.1-2, and HE.2 simulations resulted in the lowest median values of PDI, however these groups were not found to differ significantly from the default. KR.1-2 showed the highest variance, with individual plots ranging from 0.1 to over 4 PDI units.

Discussion

Historically, CIs have been utilized for predicting stem growth under various stand conditions, ranging from young even-aged conifer plantations (Brand 1986) to mature uneven aged hardwoods (Lorimer 1983). Therefore, the application of CIs in guiding thinning treatments is sensitive to stand history, species mixture, and current structure. Our results exhibit high variability in stand structure and composition across indices when applied to thinning scenarios, which arises from differences in the relative weighting scheme of individual tree competition ranking values. Trends in tree density levels across diameter classes were highly variable within each simulation, which masked any potential differences. General trends in the DD category highlight a greater retention of trees in the 70–90 cm dbh classes, which suggests a crowding pattern of small diameter trees around the focal tree across plots (Fig. 3). Despite no evidence of differences in diameter distributions of CI simulations from the standard marking guidelines in practice, there were significant changes in post-harvest basal area by species. Most of the simulations resulted in lower residual basal area of non-pine competitors than the default marking scenario, with the exception of the ME and BD indices of the DD category (Fig. 4). These patterns observed in the ME and BD indices simulations are likely due to low values of both crown

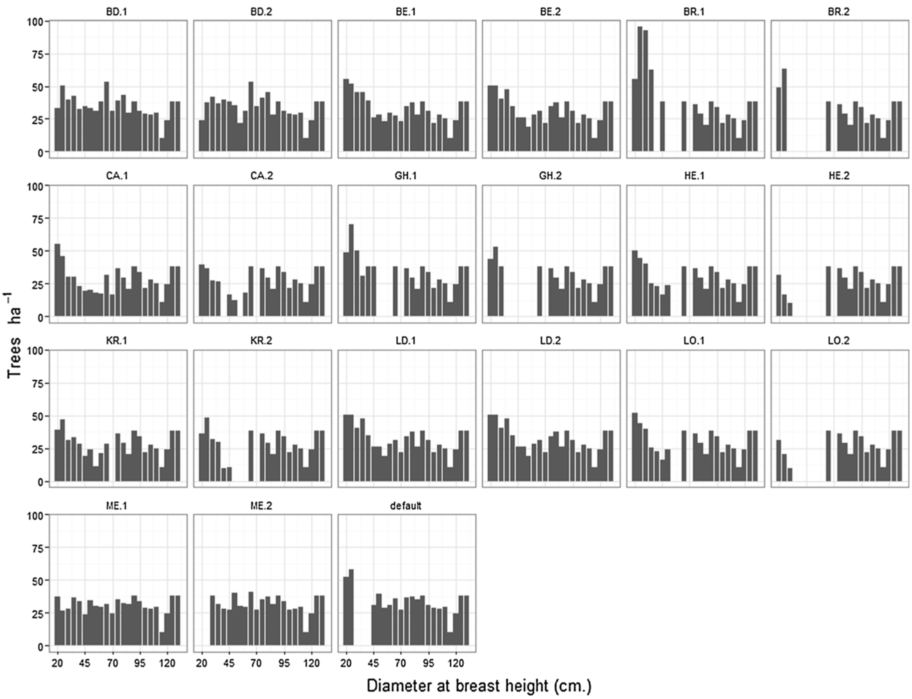

Fig. 3 Post-simulation harvest conditions of tree density (trees ha^{-1}) across competition index and harvest simulations. Trees sorted according to 5 cm. bin widths

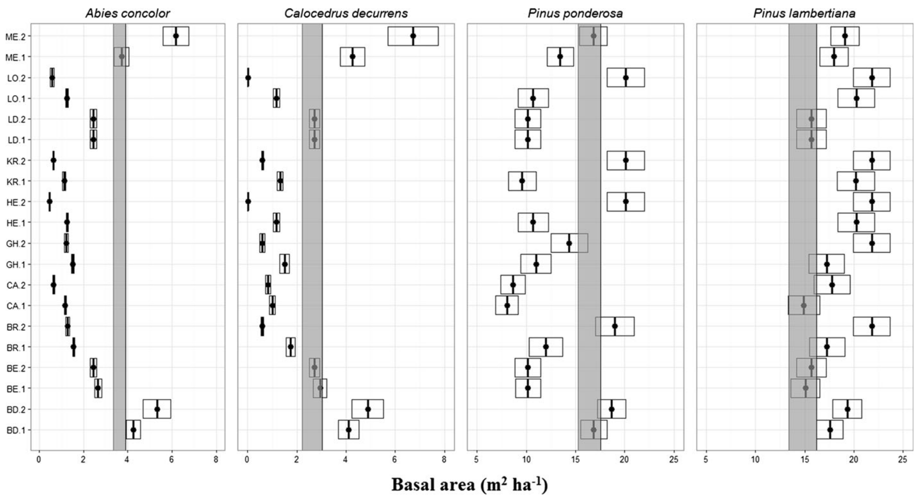

Fig. 4 Residual basal area (m^2 ha^{-1}) by species according to competition index and harvest scenario (*y* axis). *Boxes* and *circles* correspond to the 95% confidence interval and mean, respectively, while the *shaded gray region* represents the 95% confidence interval of the default marking scenario

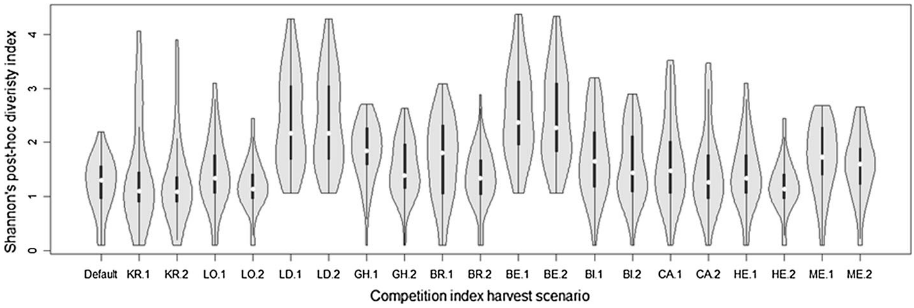

Fig. 5 Preliminary Shannon's post hoc index according to harvest simulation. *White dots* indicate the median, the *rectangle* shows the inner quantiles of the distribution of values and the outer polygon is a kernel density representation of the dataset

and height of white fir and incense cedar stems relative to the focal pine tree coupled with greater inter-tree distances. These spatial patterns of regeneration may also reflect the importance of shading by seed trees that can increase survival and recruitment of conifers on moisture limited sites (Fajardo et al. 2006). Indeed, post hoc analysis of pre-harvest inter-tree distance shows average distance between the focal pine tree to non-pine competitors at 7.9 m, while mean distance to pine stems is approximately 5.1 m, illustrating that the pine stems that are removed in the ME and BD groups (DD category) can be attributed to their proximity to the focal tree and defined integral of the probability density function. It was interesting to note that most harvest simulations resulted in a decrease of ponderosa pine basal area (Fig. 4), while those that exhibited higher levels (LO.2, HE.2, and KR.2) were consistently observed with the 2nd thinning scenario (Table 2). We speculate that these patterns are likely attributed to natural grouping patterns that characterize regeneration and recruitment of ponderosa pine (Boyden et al. 2005). Together, this suggests that there is a spatial partitioning trend as groups of pine stems grow in close proximity to the focal tree due to seed dissemination (Kinloch and Scheuner 1990; Oliver and Ryker 1990) and increased light transmittance of pine canopy architecture in comparison to white fir and incense cedar (Bigelow et al. 2011). In these simulations, the natural grouping and clumping due to seed dispersal and light conditions would favor the retention of small to mid-diameter ponderosa pine which maintain closer proximity at higher densities, therefore are defined the most competitive but retained under harvest scenario 2 (Table 2). We acknowledge that the indices evaluated here generally assume that light is the limiting factor to growth, and perhaps overlook belowground competition for resources (Burton 1993), particularly water availability at this location. Yet, manipulating the aboveground competitive neighborhood through thinning can result in favorable soil and tree water relations (Bréda et al. 1995) for the retained pine species (Hood 2010). Therefore, we expect that indices utilizing individual crown width may be most applicable to edaphic conditions encountered in our study location and in hydrologically oriented silviculture due to the casual mechanisms between crown architecture, conductance, and water availability (Tyree and Ewers 1991; Rust and Roloff 2002).

The method taken by Canham et al. (2004) of incorporating a species modifier in the CI model was expected to yield preferable residual structures and relative species dominance. In some cases, simulations resulted in the highest levels of residual basal area in the pine species with a concurrent decrease of competitors, and the LO.2 (SDI), KR.2 (DI), and HE.2 (DD) exhibited the most pronounced trends (Fig. 4). These simulations essentially shift the harvest inclusion probability toward the periphery of the plot, removing most stems in the 30–70 cm. dbh classes (Fig. 3) while retaining large, adjacent stems in close proximity to the focal and small stems at the plot perimeter. Similar to the practices proposed here, recent reports of localized focal tree release and variable density thinning (VDT) methods have been effective at achieving multiple objectives. In several instances, VDT has been reported to increase the relative proportion of under-represented species (O'Hara et al. 2012), create favorable conditions for mid canopy tree response (Comfort et al. 2010), and increase understory species diversity (Harrington et al. 2005; Aukema and Carey 2008), quadratic mean diameter, and residual growth rates (Roberts and Harrington 2008).

Stand restoration thinning invariably manipulates pre-harvest forest structure and associated variability, and traditional timber-orientated silvicultural practices result in a loss of structural heterogeneity relative to historical conditions (Ohlson and Schellhaas 2000; Russell and Jones 2001; Khai et al. 2016). Therefore, preserving structural variance after harvest remains a challenge to managers, especially when efforts are constrained to strict marking guidelines. In this study, every harvest simulation resulted in higher variance in PDI than the default marking guides (Fig. 5) which supports the beneficial utility of marking guidelines established within local relative neighborhoods. We noticed significant increases in PDI values in the BE category compared with the default. The BE index is the only one reported here that is based indirectly on inter-tree distance and uses the crown overlap between the subject and competitor, and in cases where the crown does not overlap the stem is not considered a competitor. This index appears to be sensitive to crown plasticity and canopy partitioning of mixed-species forests (Jucker et al. 2015), and simulations result in a relatively heterogeneous mixture of residual tree proportional representation (height, basal area, and species).

Sustained timber production, quality habitat for multiple avian and mammalian species, wildfire hazard mitigation, and various scales of diversity and heterogeneity are among the most cited management goals of the Sierra Nevada mixed conifer forests (Evans et al. 2011; North et al. 2009). Therefore, the value of these simulations should be assessed by their ability to achieve these objectives and their practicality. The default marking scenario removes all small to intermediate stems between 25 to 41 cm dbh in efforts to mitigate potential crowning during a wild land fire (Agee and Skinner 2005). Several of our simulations, specifically BR.2, GH.2, HE.2, and LO.2, extended this range and appear to be the most effective at removing ladder fuels through removal of fire intolerant species (HE.2 and LO.2). It should be noted that these reductions in ladder fuels and decrease in wild land fire hazard correspond to a lower PDI value. Enhancing structural variance that resembles late successional forests is commonly implemented in efforts to increase quality habitat for spotted owls (*Strix occidentalis*) (Carey et al. 1990; Weatherspoon et al. 1992) and martens (*Martes americana*) (Thompson and Colgan 1994). Therefore, variance in diversity rather than the mean value may provide a constructive compromise between wildfire mitigation and quality habitat.

We propose in scenarios where structural variance is the priority, fire behavior and fuel loads be thoroughly assessed through spatial allocation of cohorts that resemble historical patterns (Taylor and Skinner 2003; Beaty and Taylor 2008; North et al. 2009). We feel that the simulations that result in high residual pine basal area and minimal amounts of shade tolerant competitors can fulfill several objectives. These settings are conducive to establishment and up-growth of shade-intolerant pine that reflect historical structure (North et al. 2007; Hagmann et al. 2013), simultaneously facilitating a transition to conditions that favor continued dominance of pine and increased mortality of non-pine competitors (Battles et al. 2008). We emphasize that there is no clear superior simulation explored in this study that can achieve multiple desired objectives evenly, and each simulation maintains critical tradeoffs. However, we feel that the KR.2 simulation warrants further investigation given its relative decline in ladder fuels (Fig. 3), preference of pine species (Fig. 4) and high variance in PDI (Fig. 5). As the KR index is derived from spatially independent (DI) metrics and is based on tree crown width, this index maintains ease of application in the field, averting the requisite of burdensome inter-tree distance measurements during marking practices. The application of this index in thinning practices requires that single tree and group selection repeal the constraints of diameter limits, and instead prioritize crown width and potential for expansion to accelerate development of old-growth conditions (Comfort et al. 2010). A post hoc review of our inventory data shows limited variance in crown width across species explained by dbh (r^2 values for species listed as follows: white fir = 0.27; ponderosa pine = 0.50; sugar pine = 0.52; incense cedar = 0.61), therefore we feel that crown vigor and form be highlighted as a variable to consider in single tree and group selection marking, following proposed prescriptions by Harrod et al. (1999). In addition, this index could be applied with standard forest inventory datasets as it does not require explicit spatial references of neighbor trees, which is not a common metric included in operational forest inventories.

Our harvest simulations (Table 2) increased variance in structural diversity relative to the default marking guidelines (Fig. 5), yet this trend appeared to be independent of scenario. While Scenario 1 was intended to encourage residual tree BAI through the removal of stems with highest competitive status, these simulations generally decreased the density of pine species relative to Scenario 2. Therefore, the potential influence of residual structure, species mixtures, and competition on BAI remains critical to assess potential tradeoffs of these practices. We emphasize that silvicultural goals aimed to increase stem and stand growth should not be considered mutually exclusive with those that prioritize structural variance and continued pine dominance.

While our focal plot inventory estimates slightly skew the diameter distribution and basal area estimates due to the heavy inclusion of large trees in the inventory design, we feel that manipulating of focal tree neighborhood competition can be supplemented with general stand level objectives to fulfill management objectives. We emphasize that our proposed approach of using CI oriented thinning practices is limited in proportional area of the stand. Therefore, integrating gap oriented thinning with single tree/group selection at the stand level could result in irregular, highly variable conditions that resemble natural or historical stand structures (Dickinson and Cadry 2017), which in turn shift the forested landscape from distinct homogenous even aged mosaics to a complex network of multi-structured and species components (O'Hara and Nagel 2013). Utilizing marking guidelines derived from relative tree neighborhood competition dynamics could aid managers in promoting increased heterogeneity at the stand level due to the manipulation of stand structure based on hierarchical rank within groups (given variance between tree clusters) while simultaneously promoting residual tree growth. Our method is unique in that it designates trees for harvest using a competitive neighborhood single-tree selection framework, and the relative competition value of any given tree is dependent on its crown vigor and potential growing space within a defined plot area using existing legacy trees as focal anchors (Knapp et al. 2012). This hybrid of a gap-oriented single tree/group selection process in conjunction with stand-level marking guidelines is similar to those suggested by Nyland (2002), and the intensity of the thinning is modified and varies by pre-harvest structure. In practice, these approaches have been noted to increase spatial and structural heterogeneity through variable density thinning (Keyes et al. 2010), and increase the proportion of pine species (Knapp et al. 2012). Further, the integration of the thinning operations at different scales can be most operationally efficient, with silviculturists regulating specific removals in gaps throughout the stand, coupled with calibrated operator select harvest across the remaining majority area. These practices can provide a balance in achieving goals of structural variance and perceived complexity in implementation and operational costs of restoration efforts (O'Hara et al. 2012; Dickinson and Cadry 2017). We recognize that the integration of a stand-level residual basal area thinning to our gap-centric scale would enhance our proposed guidelines, therefore we hope to explore variations in stand level goals in conjunction with an expanding gap size method derived from focal-tree dimensions similar to the D + x or Dx guidelines (Smith et al. 1997; O'Hara et al. 2012). Implementing this practice requires continuous assessment of tree competition across varying spatial scales and integration with stand level prescriptions. Given the trends observed in this study, we feel that competition derived thinning strategies warrant additional investigation through simulations and field trials to assess the efficacy of implementation and sensitivity to variations in tree neighborhood and stand metrics across multiple scales.

Conclusions

Forest restoration through thinning has traditionally relied on marking guidelines confined to specific diameter limits to achieve silvicultural objectives. Mixed conifer forests of the northern Sierra Nevada are commonly managed with specific focal tree release treatments of large pine integrated with single tree and group selection across the stand matrix. We simulated harvest scenarios within focal tree release areas by removing stems of two defined competitive levels across ten common competition indices for 20 total scenarios to compare with the default marking guides. All simulations exhibited high variability in post-harvest tree density levels by size class. A total of three simulations were successful at reducing non-pine basal area while concurrently increasing pine dominance, and all harvest scenarios increased structural variance compared with the default. This method provides an alternative framework for silviculturists attempting to achieve multiple and often compounding objectives. Additional work is needed to assess these approaches in a variety of settings and across multiple scales.

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