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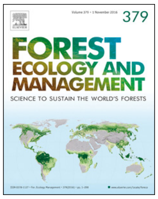

Collaborative restoration effects on forest structure in ponderosa pine-dominated forests of Colorado

Jeffery B. Cannon[a,*], Kevin J. Barrett[a], Benjamin M. Gannon[a], Robert N. Addington[b], Mike A. Battaglia[c], Paula J. Fornwalt[c], Gregory H. Aplet[d], Antony S. Cheng[a], Jeffrey L. Underhill[e], Jennifer S. Briggs[f], Peter M. Brown[g]

[a] *Colorado Forest Restoration Institute, Dept. of Forest and Rangeland Stewardship, Colorado State University, Campus Mail 1472, Fort Collins, CO 80523, USA*
[b] *The Nature Conservancy, Colorado Field Office, 2424 Spruce St., Boulder, CO 80302, USA*
[c] *USDA Forest Service, Rocky Mountain Research Station, 240 West Prospect Road, Fort Collins, CO 80526, USA*
[d] *The Wilderness Society, 1660 Wynkoop St. #850, Denver, CO 80202, USA*
[e] *USDA Forest Service, Rocky Mountain Region, 1617 Cole Blvd, Building 17, Lakewood, CO 80401, USA*
[f] *Office of Outreach and Engagement, University of Colorado Boulder, 1505 University Ave, 178 UCB, Boulder, CO 80309, USA*
[g] *Rocky Mountain Tree-Ring Research, 2901 Moore Lane, Fort Collins, CO 80526, USA*

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ABSTRACT

In response to large, severe wildfires in historically fire-adapted forests in the western US, policy initiatives, such as the USDA Forest Service's Collaborative Forest Landscape Restoration Program (CFLRP), seek to increase the pace and scale of ecological restoration. One required component of this program is collaborative adaptive management, in which monitoring data are used to iteratively evaluate and improve future management actions. Here, we assess the success of seven CFLRP treatments, implemented on 2,300 ha during the first three years of the Colorado Front Range Landscape Restoration Initiative (LRI) at achieving desired forest structure by comparing pre- and post-treatment conditions. We also compare post-treatment conditions with reconstructions of historical (ca. 1860) forest conditions to contextualize the magnitude of treatment effects. Restoration projects moved stands toward desired conditions by reducing basal area, tree density, and canopy cover and increasing average tree diameter, large gap cover, and abundance of small- to medium-sized tree groups. Post-treatment stands were similar to historical stands with respect to basal area of ponderosa pine; however, they had higher total tree density and fewer gaps than historical reference conditions, suggesting that restoration prescriptions may be improved with increased flexibility for density reduction of Douglas-fir and increased gap creation. This examination of early CFLRP treatment outcomes as they relate to desired conditions informs potential areas of adjustments to future treatments and provides baseline data to evaluate the evolution of treatments over the program's lifespan. We also identify and discuss several scientific, social, and logistical constraints to large-scale restoration success and make several recommendations to improve restoration outcomes.

1. Introduction

1.1. Background

A host of changes in land use, including grazing, logging, and fire suppression, have altered the structure and composition of many dry conifer forests of the western US over the past century, resulting in increased density in many of these forests compared to historical pre-settlement conditions (Allen et al., 2002). As a result, large, severe wildfires are increasingly affecting many ponderosa pine (*Pinus ponderosa* Douglas ex P. Lawson & C. Lawson) and other dry conifer forests of the western US with negative ecological and social consequences (Allen et al., 2002; Flannigan et al., 2013; Westerling et al., 2006). Forest restoration treatments in ponderosa pine typically focus on fuel reduction to mitigate these impacts (Covington and Moore, 1994). More recently, restoration treatment foci have expanded to address a comprehensive suite of ecological objectives such as increasing understory plant species diversity, improving wildlife habitat, enhancing landscape heterogeneity, and restoring historical fine-scale spatial patterns (Allen et al., 2002; Larson and Churchill, 2012). Large-scale US federal initiatives seek to increase extent of forest restoration on federal, state, and private lands (e.g., Charnley et al., 2011; Schultz et al., 2012). For

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[*] Corresponding author.
E-mail address: jeffery.cannon@colostate.edu (J.B. Cannon).

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example, the USDA Forest Service Collaborative Forest Landscape Restoration Program (CFLRP) is a restoration program supporting landscape-scale forest restoration and emphasizing collaborative and adaptive approaches to restoration (Schultz et al., 2012). This program emphasizes landscape-scale planning, stakeholder collaboration in the development of management goals, and an adaptive management process to monitor outcomes and provide flexibility to adjust future actions (Fernandez-Gimenez et al., 2008; Holling, 1978; Schultz et al., 2012).

Forest structure is a key component of a number of forest developmental processes. We define forest structure as composed of (1) forest density (e.g., basal area, tree density), (2) tree species composition (e.g., relative density), and (3) spatial arrangement (e.g., gap size or group size) (Franklin et al., 2002). Monitoring forest structure is a core component of adaptive management because these data are commonly collected, structural objectives are usually quantitatively defined in plans, and forest structure relates to many of the more difficult to measure restoration objectives such as decreased potential for crown fire and drought susceptibility (Fulé et al., 2012; Strahan et al., 2016). Management objectives of restoration treatments in ponderosa pine-dominated ecosystems generally focus on reducing tree density and restoring elements of composition and spatial pattern that historically characterized these stands prior to Euro-American settlement (e.g., spatial heterogeneity at multiple scales; Allen et al., 2002; Larson and Churchill, 2012). Forest spatial structure drives many forest processes such as resource availability (Boyden et al., 2012; Canham et al., 1990), regeneration dynamics (Chambers et al., 2016; Malone et al., 2018), and fire behavior (Buma, 2015; Cannon et al., 2017; Hessburg et al., 2005; Mitchell et al., 2009). Reconstructions of historical forest density, composition, and spatial patterns are often examined to infer historical range of variability of forest structure and as a reference to guide restoration efforts (Aplet and Keeton, 1999; Keane et al., 2009; Mast et al., 1999; Moore et al., 1999; Romme et al., 2003; Veblen, 2003; Waltz et al., 2003). Comparing restoration outcomes to desired conditions of restoration programs can identify areas of improvement in relevant terms for future prescription development. Comparing outcomes of restoration treatments to historical reference conditions can provide context for understanding the degree of change in forest structure accomplished by restoration treatments. Such comparisons highlight potential areas of adjustment of restoration treatment prescriptions to better achieve congruency with historical conditions; thus providing a critical linkage to a program of adaptive management (Aplet and Keeton, 1999; Keane et al., 2009). In addition, comparisons to historical data can promote consideration of restoration objectives in the context of future climatic scenarios, potentially with shifting species ranges and disturbance regimes (Aplet and Keeton, 1999; Keane et al., 2009). Here, we examine outcomes of one CFLRP landscape-scale program implemented in ponderosa pine forests of the Colorado Front Range to assess management objectives and to provide insights for implementing an adaptive management process in the context of large-scale forest restoration initiatives.

1.2. Colorado Front Range Landscape Restoration Initiative (LRI)

The Front Range Roundtable, a multi-stakeholder collaborative group in Colorado, identified 162,000 ha of ponderosa pine-dominated forests as priority areas where ecological restoration and fire risk mitigation needs overlapped (Cheng et al., 2015; FRFTPR, 2006). This collaborative group was selected as a CFLRP grant recipient in federal fiscal year 2010 to implement the Colorado Front Range Landscape Restoration Initiative (LRI) with a treatment goal of 13,000 ha implemented over a 10-year period. The program has funded implementation of restoration treatments across the Arapaho and Roosevelt National Forests and the Pike and San Isabel National Forests. To address the complex restoration objectives, diverse stakeholders, and large geographic extent of the LRI, the group collaboratively developed desired conditions (Dickinson and SHSFRR, 2014), a monitoring plan (Addington et al., 2018; Barrett et al., 2017; Clement and Brown, 2011), and an adaptive management plan to assess program outcomes (Aplet et al., 2014).

Although the history of fire and forest establishment is relatively well-studied in Front Range forests (Brown et al., 2015, 1999; Donnegan et al., 2001; Ehle and Baker, 2003; Kaufmann et al., 2000; Schoennagel et al., 2011; Sherriff and Veblen, 2007; Williams and Baker, 2012), limited quantitative data on historical forest density, composition, and spatial pattern were available at a geographic extent appropriate for informing decisions about stand-scale desired conditions. Thus, a general set of qualitative desired conditions of the LRI was developed based on a synthesis of scientific literature on fire history and forest establishment, supplemented with historical descriptions and photographs (Jack, 1900; Kaufmann et al., 2001; Veblen and Lorenz, 1991), management guidelines from southwestern US ponderosa pine systems (Reynolds et al., 2013), and the expertise of collaborating scientists and practitioners. The desired conditions of the LRI pertaining to stand-scale forest structure include the following (Addington et al., 2018; Dickinson and SHSFRR, 2014):

- Low-density forest patches and openings should predominate on lower productivity or drier sites and lower elevations; higher density patches should predominate on higher productivity or wetter sites, and higher elevations.
- Lower productivity sites should be highly dominated by ponderosa pine; higher productivity sites should have greater species diversity with higher Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) abundance and other species present to varying degrees.
- All stands should contain a mosaic of openings, groups of trees, and isolated trees; on lower productivity sites, openings and isolated trees should occur more frequently; on higher productivity sites, larger tree groups should occur more frequently.

Previous studies have documented aspects of some LRI restoration treatments. Underhill et al. (2014) found that early treatments reduced tree density and increased canopy openness. Briggs et al. (2017) found that treatments altered forest structure in accordance with desired conditions, although not all metrics of spatial heterogeneity increased; these authors also documented no increase in exotic understory plants and no decreased use by certain wildlife species. Dickinson et al. (2016) used remote sensing techniques to map forest canopy and openings and found that LRI treatments reduced canopy cover and increased some metrics of spatial heterogeneity. At the time of these studies, detailed information on historical forest structure was not available, making it difficult to contextualize the magnitude of changes in forest density, composition, and spatial pattern of restoration treatments.

1.3. Research objectives

Here, we analyze pre- and post-treatment data from early (2010–2013) restoration treatments of the Colorado Front Range LRI to a) assess whether they achieved desired conditions, and b) compare treatment outcomes to recently available reconstructions of historical (1860) conditions (Battaglia et al., 2018a; Brown et al., 2015). Because detailed historical data were not available for reference at the time the LRI drafted their initial desired conditions, our presentation of the differences between post-treatment and historical conditions should not be viewed as evaluative or judgmental of individuals or institutions. Rather, they provide valuable insights towards understanding the effectiveness of past restoration treatments and improving the effectiveness of future implementation. Comparisons between treatment outcomes and historical data advance the adaptive management process of the LRI and more generally provide insights into constraints of the adaptive management process in the context of large-scale forest restoration initiatives.

2. Methods

2.1. Study area

The montane forests of the eastern slope of the Colorado Front Range consist of forest types ranging from ponderosa pine-dominated woodlands in the lower montane zone (approximate range of 1600–2600 m depending on latitude) to ponderosa pine forests with increasing proportions of Douglas-fir in the upper montane zone (approximate range of 2300–2900 m, depending on latitude) which also include intermixing quaking aspen (*Populus tremuloides* Michx.), limber pine (*Pinus flexilis* James), and lodgepole pine (*Pinus contorta* Douglas ex Loudon) (Kaufmann et al., 2006). Early LRI restoration treatments were completed between 2010 and 2013 in ponderosa pine-dominated forests spanning elevations from 2200 to 2900 m. LRI treatments focused on removal of smaller-diameter trees ($<$ 30 cm dbh) with an emphasis on enhancing spatial heterogeneity and increasing dominance of ponderosa pine over other conifers. Specific objectives of individual restoration treatments varied based on factors such as pre-existing forest conditions and topography. In addition, most treatments of the early LRI were implemented in forest stands approved under a previous planning decision; thus, planning considerations imposed constraints on what management options were implementable in early treatments. Such constraints included restrictions on creation of large gaps, for example. Thus, treatments were conducted using a combination of mechanized equipment and manual thinning, and implementation methods varied within and among projects. Project areas examined include three restoration treatments in the Pike San Isabel National Forest, and four restoration treatments in the Arapaho Roosevelt National Forest (Fig. 1).

2.2. Included datasets

2.2.1. Pre- and post-treatment data

Consistent with the LRI monitoring plan (Clement and Brown 2011), we utilized Common Stand Exam (CSE) data (USDA Forest Service, 2015) to evaluate the effects of restoration treatments on forest density and composition. CSE data is collected using standardized inventory procedures prior to USFS management activities. Inventory data were collected 1 to 2 years before and after each LRI treatment, providing a large dataset of pre- and post-treatment forest density, tree size, and tree composition (Fig. 2A) at 525 variable radius plots representing 2300 ha of restoration treatments. Plots were placed within stand boundaries using CSE protocols and averaged a density of approximately 1 plot per 4.38 ha. Each CSE plot samples overstory trees ($>$ 12.7 cm (5 in) dbh) using a variable radius plot, and samples smaller trees in three 16.2 m^2 (2.27 m radius) subplots. To facilitate comparisons between CSE plots and historical data (discussed below), we removed from consideration all trees $<$ 4 cm dbh. We summarized tree list data to obtain plot level estimates of the following metrics of forest density and composition: (1) total basal area, (2) total tree density, (3) quadratic mean diameter, (4) ponderosa pine basal area, and (5) Douglas-fir basal area.

We evaluated restoration treatment effects on fine-scale spatial patterns using analysis of satellite imagery. Imagery was acquired from WorldView-02, GeoEye-01, and Quickbird-02 satellites with spatial resolutions between 1.65 and 2.16 m and spectral resolutions of 4 to 8 bands. We acquired the highest resolution imagery available within 1 to

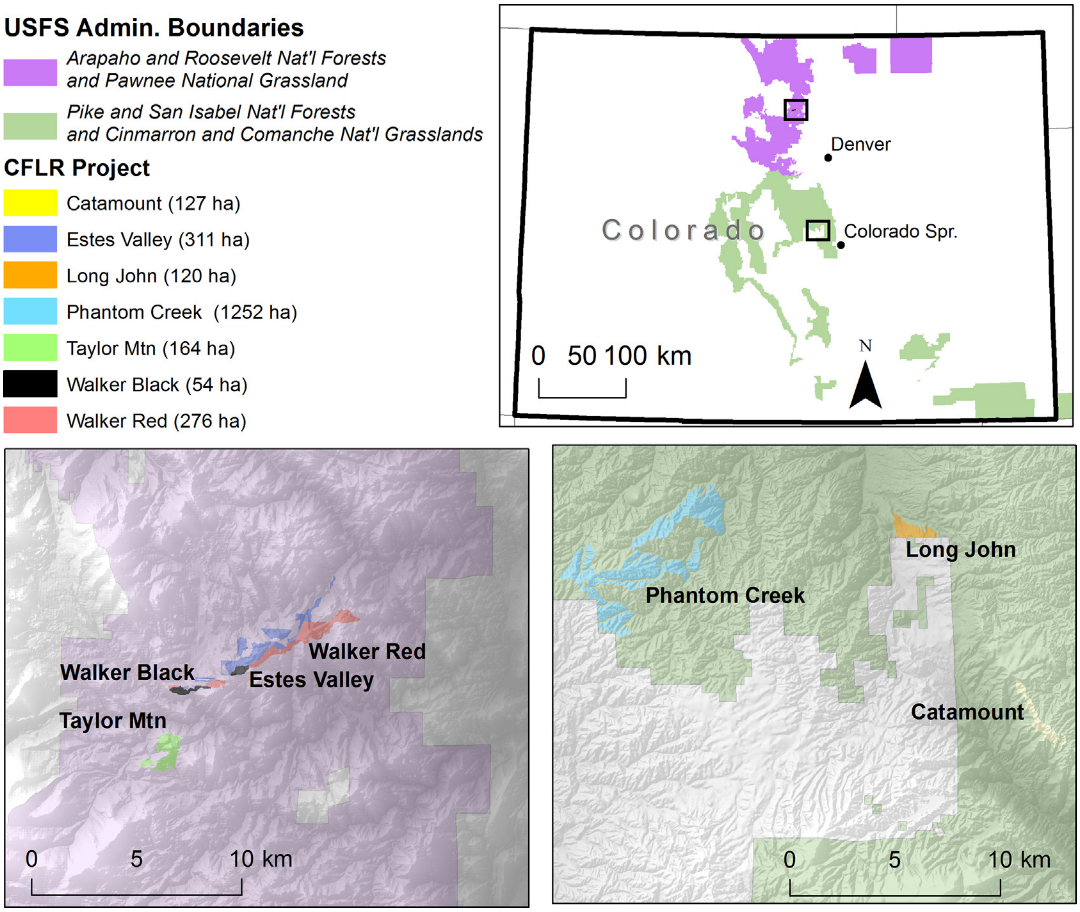

Fig. 1. Map of project areas included in the study, including four project areas from the Arapaho and Roosevelt National Forests & Pawnee National Grassland and three projects from the Pike and San Isabel National Forests & Cimarron and Comanche National Grasslands.

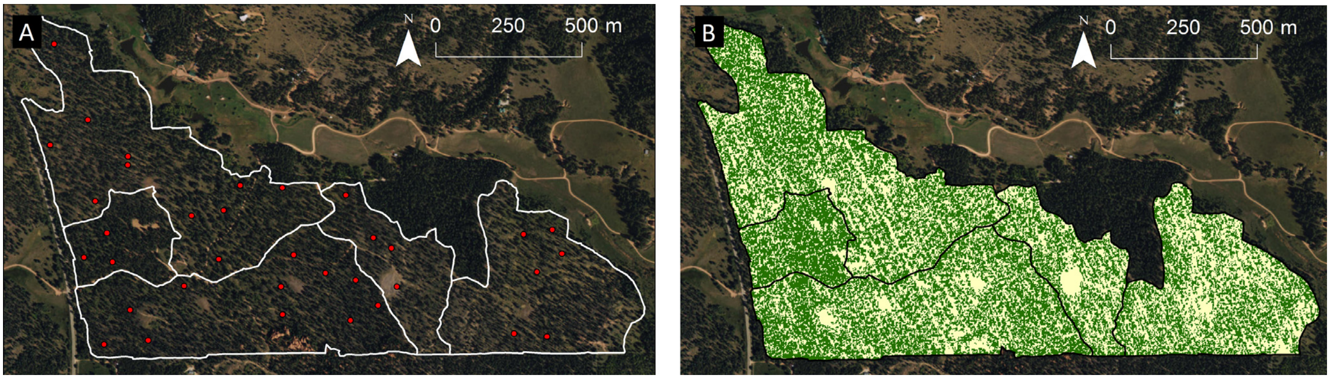

Fig. 2. Map of Long John project area located within the Pike and San Isabel National Forests illustrating (A) locations of survey plots where pre- and post-treatment forest inventory sampling was completed and (B) canopy cover classification of post-treatment conditions.

2 years of treatment dates that was suitable for classification (cloud-free, snow-free, leaf-on, near-anniversary; Fig. 2A). All satellite imagery was georeferenced using base imagery available in ArcMap and digital elevation models and was resampled to 3 m using bilinear interpolation to facilitate comparisons among images (Lillesand et al., 2015; Turner, 2001). For each image, we derived the normalized difference vegetation index (NDVI; [Near infrared$_1$ – Red]/[Near infrared$_1$ + Red]), simple ratio (Near infrared$_1$/Red), and red to green ratio (Red/Green) to improve classification (Lillesand et al., 2015). We trained the classification by stratifying approximately 90 training polygons across each image and categorized each training area as canopy, opening, or shadow. Training areas averaged 269 m^2 in size (i.e., contained ~30 pixels). Training areas were used to create spectral signatures and the image was classified into canopy, opening, and shadows using maximum likelihood classification. Additional training categories were added where necessary to account for anomalous spectral signatures (e.g., yellow aspen, bare soil, etc.) and reclassified as canopy or opening following classification, as appropriate. Areas initially classified as shadows exhibited a bimodal distribution of NDVI and could be reclassified as either canopy or openings by thresholding the local minimum frequency NDVI using gray-level thresholding of NDVI (Lillesand et al., 2015). All imagery classification was completed using ArcMap 10.4. Classification of satellite imagery produced 3 m resolution rasters of canopy cover and openings (Fig. 2B). To verify the classification, we used k-fold internal cross validation approach (k = 5). Each satellite image was classified as above using a subset (80%) of the training plots and withholding a smaller subset (20%) to internally verify each classification, and repeated five times for each image withholding a different set of training areas in each instance. We compared withheld and included training areas to calculate an error matrix and kappa coefficient ($\hat{k}$) to evaluate the supervised classification (Congalton and Green, 2009).

The classified rasters were further processed using the raster package (Hijmans and van Etten, 2016) in R. We calculated canopy cover (proportion of pixels identified as canopy) and identified portions of each image in "large gaps," defined as any continuous opening > 18 m across the smallest dimension (Fig. 3A and B). This minimum diameter was chosen based on a studies by Boyden et al. (2012) and Boyden and Binkley (2015), which found that neighborhoods between 9 and 20 m in radius were important for predicting resource abundance (light, N, and P) and tree growth. We identified large gaps using a simplified version of the PatchMorph algorithm (Girvetz and Greco, 2007), identifying all openings > 9 m from canopy and buffering these areas outward 9 m to represent the extended gap area concept (Runkle, 1982). Classified rasters were also processed to evaluate tree spatial distribution by patch size. Note that our definition of "large gap" refers only to openings large enough to contain interior portions of openings > 9 m from canopy, and that this term is distinct from "openness," which refers simply to the complement of canopy cover at any distance from trees (i.e., any area not covered by canopy). Although many studies describe group size in terms of tree counts (e.g., Larson and Churchill, 2012), it is not consistently possible to identify individual trees using satellite imagery; thus, we classified continuous patches of canopy using a patch size criterion. Continuous patches of canopy were identified using a 4-pixel neighbor rule (e.g., continuity measured among neighboring pixels with a shared orthogonal edge). Patches were then binned into patch size classes analogous to mature tree group sizes used in Churchill et al. (2013) with an assumed crown size of 28.3 m^2 (3 m radius). Patches were classified as isolated (< 56 m^2, i.e., < approx. two mature trees), small patches (56–113 m^2, approx. 2–4 mature trees), medium patches (141–254 m^2, approx. 5–9 mature trees), and large patches (> 283 m^2, approx. 10+ mature trees). See Fig. 3C and D for an illustration of tree patch size classification.

For each plot, we used classified imagery to extract spatial metrics from rasters in a 0.22 ha circular sampling area centered over the location of existing CSE plots (circular sampling areas in Fig. 3). Plot sizes were selected to match the size of historical reconstruction plots (discussed below). Within the 0.22 ha sampling areas, we summarized spatial pattern metrics including (1) canopy cover (as a percentage of plot area), (2) cover of large gaps (as a percentage of plot area), (3) presence of large gaps (0 or 1), (4) distribution of tree patch sizes (i.e., proportions of sampling area classified as isolated, small, medium, and large tree patches), and (5) canopy aggregation index (unitless). Canopy aggregation index indicates the level of aggregation of canopy in the sampling area relative to the maximum possible aggregation (McGarigal et al., 2012), calculated using the SDMTools package (VanDerWal et al., 2014) in R (R Core Team, 2017).

2.2.2. Historical reconstruction data

Recently, a dendrochronology-based forest reconstruction network in the Front Range was established with the goal of informing restoration activities in ponderosa pine forests in this area (Battaglia et al., 2018b; Brown et al., 2015). The size and geographic range of this network provides a broad view of forest structures present historically and how they varied across biophysical settings. An 1860 reconstruction date approximates the start of Euro-American settlement in the region, which brought logging, mining, grazing, and later fire suppression, and is the earliest date when historical evidence could be expected to still be present in most areas (Brown et al., 2015). Detailed methodological details are presented in Brown et al. (2015) and Battaglia et al. (2018b). Here, we summarize methods relevant to the context of this study.

This dataset includes 163 half ha plots distributed across 26 landscapes of approximately 1250 ha located across the lower and upper montane zones. Seven plots from forests in Wyoming were excluded from comparison with treatment outcomes of the LRI. Sampling was random within forested areas of the landscapes that could

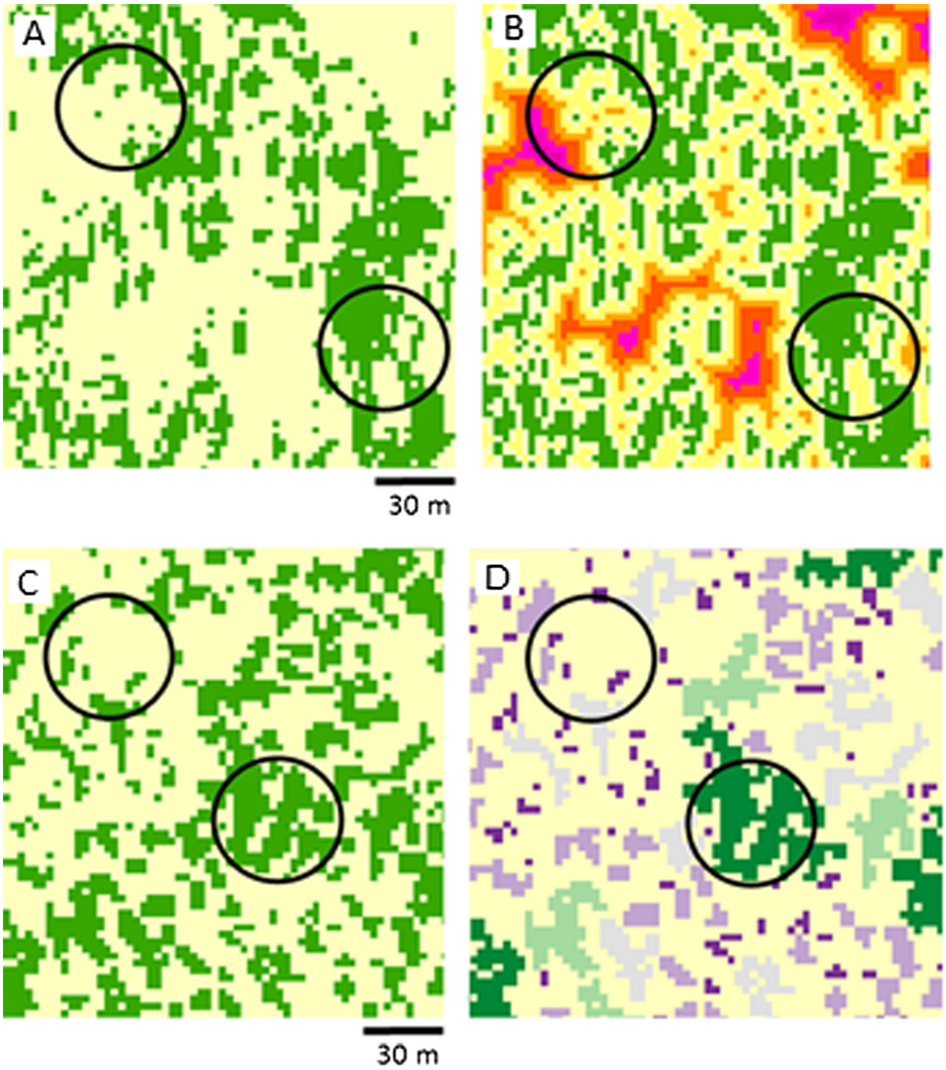

Fig. 3. Example portions of 3-m resolution canopy cover classification (A and C); green pixels represent canopy cover, and pale yellow pixels indicate openings. (B) Canopy cover classification from A with openings overlaid with colors indicating increasing Euclidean distance from canopy (orange-to- red shading). (D) canopy cover classification from C with contiguous areas of canopy cover classified according to increasing patch size: smallest patches are indicated in dark purple, and largest patches are indicated in dark green. Black circles represent locations of sampling areas where spatial data were extracted to link to co-located ground plots.

accommodate a 0.5 ha square plot on relatively uniform aspect and slope (≤40%). Within the 0.5 ha plot, all live trees and remnants (stumps, logs, and snags) were identified based on size and morphology criteria (Huckaby et al., 2003a, 2003b) and mapped. Detailed dendrochronology sampling was completed on four circular subplots (0.2 ha total area) per plot to reconstruct historical (1860) basal area, density, and species composition. Dendrochronology data from the subplots were used to refine morphological field classifications of stem-mapped live trees in the larger plot into pre- and post-settlement classes by means of a multiple logistic regression equation with a random effect for plot. This was done because morphology and size criteria varied in effectiveness at distinguishing pre- versus post-settlement trees across the wide range of environmental and stand conditions. Using the ages of trees obtained from cores allowed verification of the accuracy of the classification of trees as pre- vs. post-settlement based on the field observations of their size and morphology characteristics. All plots were included in analyses of forest density and composition. However, for spatial pattern analysis only plots with high morphological classification accuracy (> 70% producers or user's accuracy) were included in the spatial dataset, resulting in a total of 163 plots used in density and composition analyses and 100 plots carried forward into spatial analyses. For the subset of 100 plots used for spatial analysis, stem maps were converted into rasterized maps of canopy cover for comparison to classified rasters of treated areas. Mapped stems of historical trees were buffered 3 m to simulate canopy cover (Larson and Churchill, 2012) and the resulting polygons were converted to classified rasters denoting canopy cover or openings. A 3 m radius represents a simplification of the variability in actual crown widths as historical crown widths are unknown and may differ from contemporary estimates. However, exploratory analyses confirmed that the relationship between historical basal area and canopy cover derived from a 3 m radius assumption did not differ from the relationship of contemporary basal area measured from CSE plots and canopy cover estimates derived from remote sensing in our dataset. In addition, a 3 m crown radius corresponds to an inter-tree distance of 6 m, facilitating comparisons of tree patch sizes distributions to those presented in similar studies (e.g., Brown et al., 2015; Larson and Churchill, 2012; Tinkham et al., 2017). Historical rasters were processed in the same manner as the remotely sensed rasters of LRI treatment areas to identify canopy cover and large gap metrics along with distribution of tree group sizes. To minimize edge effects in analyses, the spatial metrics outlined above were extracted from a circular sampling area of 0.22 ha centered on each plot after excluding a 9 m buffer around the perimeter.

Table 1
Number of observed sites summarized by elevation, aspect, and condition. Plot data from ground-collected data in CFLR projects and historical conditions were pooled by project/landscape, aspect, and elevation zone and summarized to produce the following number of sites to use in statistical comparisons.

Data type	Elevation zone	Aspect	Number of sites		
			Pre-treatment	Post-treatment	Historical
Density and composition	Lower montane	Wet	13	13	15
		Dry	9	9	12
	Upper montane	Wet	19	19	15
		Dry	24	26	17
	Total		65	67	59
Spatial structure	Lower montane	Wet	12	12	11
		Dry	9	9	11
	Upper montane	Wet	19	19	12
		Dry	24	26	16
	Total		64	66	50

2.3. Data compilation and analysis

Topographic data were summarized for each plot in the treatment and historical datasets to examine the influence of these gradients on treatment outcomes. We classified plots as lower or upper montane per Kaufmann et al. (2006). The description of desired conditions for the LRI (Addington et al., 2018; Dickinson and SHSFRR, 2014) emphasizes aspect as a driver of forest structure through influence on water balance and productivity. Thus, we classified plots based on solar radiation in ArcGIS, which accounts for incidence angles of solar radiation throughout the year and topographic shadowing (Fu and Rich, 2002). This method generally matches an aspect-based classification but accounts for interactions between solar radiation and slope angle. We classified plots as wet aspects (above the median solar radiation; 1607 kW-h m^{-2}) and dry aspects (below the median solar radiation).

Data on forest structure were compiled for each of the total of 688 plots (525 CSE plots and 163 historical reconstruction plots). However, not all plots had a full complement of pre- and post-treatment forest structure data (Table 1). Thus, analyses for components of forest structure were completed for slightly different sets of plots depending on which data were available. To avoid pseudo-replication in statistical analyses, data from individual projects were summarized by treatment unit (as delineated by the USFS), aspect (wet or dry aspects), and elevation zone (upper or lower montane). Summarizing large gap presence (0 or 1) among all plots within a treatment unit resulted in a binomial variable (hereafter referred to as "large gap frequency") expressed as the percentage of plots containing large gaps. Summary information on observational units in each class is presented in Table 1. Historical conditions were summarized by the landscape unit in which they occurred. This summary resulted in a final set of data used for statistical analyses containing (1) a forest density and composition dataset with 65 pre-treatment units, 67 post-treatment units, and 59 historical units and (2) a forest spatial dataset with 64 pre-treatment units, 66 post-treatment units, and 50 historical units (Table 1).

Our analyses sought to determine how LRI projects altered forest structure and how post-treatment conditions compared to historical conditions in similar topographic settings rather than emphasize particular changes in paired pre- and post-treatment plots. Thus, we used analysis of variance (ANOVA) to test for significant differences in forest structure among three forest "conditions" (pre-treatment, post-treatment, and historical), and included categorical factors to account for elevation zone (upper vs. lower montane) and aspect (wet vs. dry) using R. ANOVA models took the following form: response variable ~ condition + elevation + aspect + condition:elevation + condition:aspect. The main effects of elevation and aspect were included to control for topographic impacts on response variables, but the primary factors of interest were the main effect of condition and the interaction between condition and topographic factors (elevation zone and aspect). Full ANOVA tables are reported in Tables S1 and S2). When condition effects were significant, we used Tukey's honest significant difference tests to contrast conditions using the lsmeans package in R (Lenth, 2016). All response variables were analyzed in this manner except that (1) large gap frequency was analyzed using logistic multiple regression to account for the binomial variable, and (2) we included canopy cover as a covariate when analyzing aggregation index as these two variables are strongly correlated (McGarigal et al., 2012). After determining that aggregation index significantly differed between conditions, we used a multivariate ordination technique to produce a visual summary of tree patch size distribution (i.e., proportion of canopy cover in isolated, small, medium, or large patches). We performed non-metric multidimensional scaling (NMS) using the metaMDS function in the vegan package (Oksanen et al., 2016) in R. This ordination technique was used to produce a two-dimensional solution using Bray–Curtis distances in the input distance matrix on all observational units. Results were plotted and overlaid with correlation vectors, condition means, and standard deviations to aid in interpretation. We generated an additional biplot summarizing NMS axis means by condition and aspect to investigate how spatial structure relates to aspect in pre-treatment, post-treatment, and historical stands.

3. Results

3.1. Forest density and tree size

Early LRI treatments led to decreased basal area and tree density relative to pre-treatment conditions (Table 2; Fig. 4A and B; Table S1). Mean basal area significantly differed among conditions (pre-treatment, post-treatment, and historical; $F_{2,182} = 49.95$, $p < 0.001$). Tukey's honest significant difference tests indicated that mean basal area was reduced 35% (from 21.1 to 13.6 $\mathrm{m}^2\ \mathrm{ha}^{-1}$) following restoration treatments ($p < 0.001$), which was higher than historical stands ($p < 0.001$; Fig. 4A. Similarly, tree density differed among conditions ($F_{2,182} = 46.43$, $p < 0.001$) and mean tree density was significantly reduced 53% (from 716 to 333 ha^{-1}; $p < 0.001$) following restoration treatments, which remained more than two times greater than in historical stands (158 ha^{-1}, $p = 0.009$; Fig. 4B).

Tree density also had a significant condition by aspect interaction ($F_{2,182} = 9.22$, $p < 0.001$; Table S1). Pre-treatment tree density was generally higher on wet sites relative to dry sites (Fig. 4C). Post-treatment tree density was approximately 2.2 times higher than historical densities on wet aspects, and only 2 times higher on dry aspects (Fig. 4C). Quadratic mean diameter did not differ significantly among conditions (Fig. 4D; Table 2, $\mathrm{F2}_{,182} = 1.77$, $p = 0.195$).

3.2. Tree composition

LRI treatments reduced basal area of ponderosa pine and Douglas-fir in similar proportions, but the degree of similarity between post-treatment and historical composition varied by topographic position. Ponderosa pine basal area differed among conditions ($F_{2,182} = 6.90$, $p = 0.001$, Fig. 5A; Table S1). LRI treatments reduced mean ponderosa pine basal area 28% (from 11 $\mathrm{m}^2\ \mathrm{ha}^{-1}$ pre-treatment to 8.0 $\mathrm{m}^2\ \mathrm{ha}^{-1}$ post-treatment; $p = 0.002$, Fig. 5A), such that they were not significantly different from historical ponderosa pine basal area (6.7 $\mathrm{m}^2\ \mathrm{ha}^{-1}$; $\mathrm{p} = 0.207$, Fig. 5A). Ponderosa pine basal area showed a significant condition by elevation interaction ($F_{2,182} = 4.32$, $p = 0.015$), with mean ponderosa pine basal area within 1% of historical levels in upper elevation sites, but over 50% greater than historical conditions

Table 2
Mean structure, composition, and spatial metrics summarized by elevation zone (upper vs. lower montane) and aspect (wet vs. dry). Values in parentheses indicate 1 s.d. of the mean value.

	Lower montane					
	Wet sites			Dry sites		
Structural Metric	Pre-treatment	Post-treatment	Historical	Pre-treatment	Post-treatment	Historical
Basal area ($m^2\,ha^{-1}$)	23.8 (8)	14.3 (4.8)	6.8 (4.2)	19.8 (5.9)	13.6 (3.5)	7.1 (3.5)
Tree density (ha^{-1})	920 (484)	348 (200)	143 (98)	491 (215)	240 (90)	125 (86)
Quadratic mean diameter (cm)	22.1 (6.4)	27.1 (7.4)	24.6 (3.9)	26.6 (6.4)	29.8 (6.8)	29.8 (9.6)
P. ponderosa basal area ($m^2\,ha^{-1}$)	12.4 (8.5)	8.1 (4.7)	5.7 (3.6)	15.1 (8.6)	10.7 (6.3)	6.2 (3.6)
P. menziesii basal area ($m^2\,ha^{-1}$)	6.8 (5.2)	4.6 (3.7)	1 (1)	3.6 (4.1)	2.9 (4.4)	0.8 (1.2)
Canopy cover (%)	71.2 (11.8)	41.7 (14.9)	33.3 (20.5)	51.3 (22.7)	39 (23.9)	28.1 (15)
Large gap cover (%)	4.2 (5.4)	11.7 (13.6)	31.2 (33.9)	19 (25.7)	26.6 (36.1)	38.9 (28.8)
Gap frequency (%)	17.2 (22)	49.7 (41.1)	63.6 (50.5)	51.5 (47.1)	53.7 (47)	88.6 (30.3)
Aggregation index (unitless)*	81.7 (6.6)	60.3 (11.7)	61.8 (8.5)	70.1 (12.1)	63 (11.1)	57.9 (8.1)
	Upper montane					
	Wet sites			Dry sites		
Structural Metric	Pre-treatment	Post-treatment	Historical	Pre-treatment	Post-treatment	Historical
Basal area ($m^2\,ha^{-1}$)	21.6 (5.7)	13.2 (4.6)	9 (3.8)	19.7 (5.5)	13.6 (4.9)	10 (5.3)
Tree density (ha^{-1})	918 (392)	424 (302)	202 (166)	532 (234)	290 (198)	156 (102)
Quadratic mean diameter (cm)	20.8 (3.5)	26.3 (8.8)	26.9 (5.6)	25.3 (7.4)	31.1 (10.4)	31.1 (6.3)
P. ponderosa basal area ($m^2\,ha^{-1}$)	6.9 (5.1)	4.8 (3.3)	6.4 (3.2)	12.1 (6.3)	9.3 (4.5)	8.2 (4.9)
P. menziesii basal area ($m^2\,ha^{-1}$)	6.5 (4.7)	4.8 (1.8)	2 (3.2)	3.5 (3.6)	2.5 (2.1)	1 (1.4)
Canopy cover (%)	77.1 (12.8)	36.3 (14.6)	41.8 (21.5)	57.9 (19)	38.5 (19.7)	31.5 (15.7)
Large gap cover (%)	1.9 (4.8)	18.6 (21.6)	15.7 (19.4)	11.9 (22.2)	22.3 (25.1)	30.8 (29.2)
Gap frequency (%)	11.6 (24.8)	57.6 (39.7)	69.2 (44.2)	39.5 (39.5)	57 (40.5)	72.5 (34.9)
Aggregation index (unitless)*	84.7 (7.3)	55.3 (10.6)	66.4 (11.6)	77.2 (8.4)	61.9 (14.2)	60.8 (6.7)

on lower elevation sites (Fig. 5B).

Douglas-fir basal area differed among conditions ($F_{2,182} = 15.24$, $p < 0.001$, Fig. 5C; Table S1), with LRI treatments decreasing mean Douglas-fir basal area 28% (from 5.1 pre-treatment to 3.6 $m^2\,ha^{-1}$, $p = 0.040$, Fig. 5C). However, post treatment Douglas-fir basal area remained nearly three times higher than historical conditions which had a mean of 1.2 $m^2\,ha^{-1}$ ($p = 0.001$, Fig. 5C).

3.3. Fine-scale spatial pattern

The *k*-fold cross validation of satellite imagery indicated that remote classification had an overall accuracy of 90.7% with a kappa coefficient ($\hat{k}$) of 0.780 indicating moderately-strong agreement between classified canopy rasters and independently classified training areas ($p < 0.0001$; see confusion matrix in Table S3; Congalton and Green, 2009; Landis and Koch, 1977). Mean canopy cover differed among conditions ($F_{2,171} = 20.33$, $p < 0.001$; Table S2). LRI treatments reduced canopy cover from 65% to 39% ($p < 0.001$) which did not differ significantly from historical conditions (34%; $p = 0.248$; Fig. 6A). A significant condition by aspect interaction ($F_{2,171} = 5.21$, $p = 0.006$) indicated that canopy cover closely approached that of historical conditions on wet sites (38.4 vs. 37.7%), but was greater than historical conditions on dry sites, albeit not significantly so (38.7 vs 30.1%; Fig. 6B).

The extent of area covered by large gaps varied among conditions ($F_{2,171} = 4.17$, $p = 0.017$; Table S2). Large gaps increased from covering 8% of pre-treatment stands to 20% of post-treatment stands ($p = 0.049$), which in turn did not differ from historical conditions of 29% ($p = 0.074$; Fig. 6C). Although not significant at the $\alpha = 0.05$ level, this 9 percentage point difference is rather large relative to the post-treatment historical conditions of 29%. In addition, the frequency of large gaps varied among treatments ($\chi^2 = 44.13$, df = 2, $p < 0.001$). Large gap frequency (the proportion of plots within treatment units or historical landscape units that contained at least one gap) also varied among conditions. LRI treatments increased the frequency of large gaps from 29% to 55% ($p < 0.001$); but this frequency remained significantly lower than in historical conditions where 73% of plots contained large gaps ($p < 0.001$, Fig. 6D). Neither aspect nor elevation interacted significantly with condition to predict large gap frequency ($F_{2,171} = 2.66$, $p = 0.073$ and $F_{2,171} = 0.84$, $p = 0.435$, respectively).

Overall, canopy aggregation index varied significantly among conditions ($F_{2,170} = 8.32$, $p < 0.001$; Table S2). LRI treatments decreased aggregation index from 79.3 to 61.7 ($p < 0.001$), which was not distinguishable from the historical aggregation index of 59.8. ($p = 0.538$). A significant condition by aspect interaction indicated that the reduced aggregation was more pronounced on wet sites relative to dry sites ($F_{2,170} = 5.56$, $p = 0.005$, Fig. 7A and B), especially in stands with lower canopy cover (5–30%, Fig. 7A). These results suggest that post-treatment wet stands may contain proportionally more single trees at the expense of small- or medium-sized patches of trees. NMS ordination plots and correlation vectors indicated that an increase along NMS axis 1 is correlated with higher proportions of large canopy patches and a subsequent reduction in patches of smaller size classes (Fig. 7C and D). An increase along NMS axis 2 is associated with an increase in small- and medium-sized patches relative to isolated trees. Early LRI treatments dissected large tree clumps into many smaller isolated trees (e.g., leftward shift between pre- and post-treatment means along NMS axis 1, Fig. 7C). However, large tree patches remained in higher abundance in post-treatment stands compared to historical conditions. Ordination analysis indicated a large range of variation in abundance of small-, medium-, and large- patches in historical conditions (variation along NMS axis 2), but lower variation in abundance of these patches in pre- and post-treatment stands. Ordination analysis suggests differences in structural variability between wet and dry aspects (i.e., wet and dry units separate along NMS axis 2), with wet historical forests exhibiting lower levels of isolated trees and higher representation of small-to-medium tree groups than dry historical forests (Fig. 7D). However, wet and dry sites in post-treatment stands do not exhibit such variation and the mean conditions of wet and dry sites

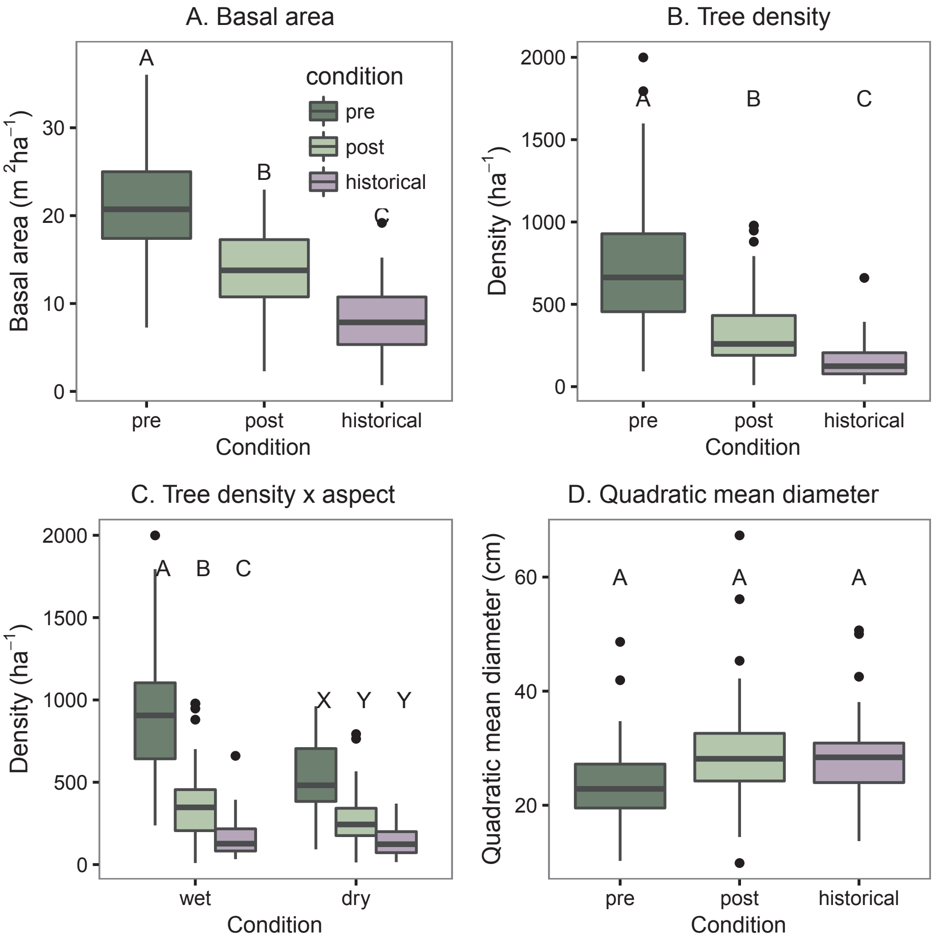

Fig. 4. Boxplots comparing pre- and post-treatment structural metrics to historical conditions, including (A) basal area and (B) tree density, along with comparisons of (C) tree density summarized by aspect and (D) quadratic mean diameter. Conditions not sharing a letter are significantly different (Tukey's honest significant difference, $p_{adj} < 0.05$). In panels C and D, *post hoc* Tukey's tests were conducted separately for wet and dry aspects due to a significant interactive effect. See text for full details.

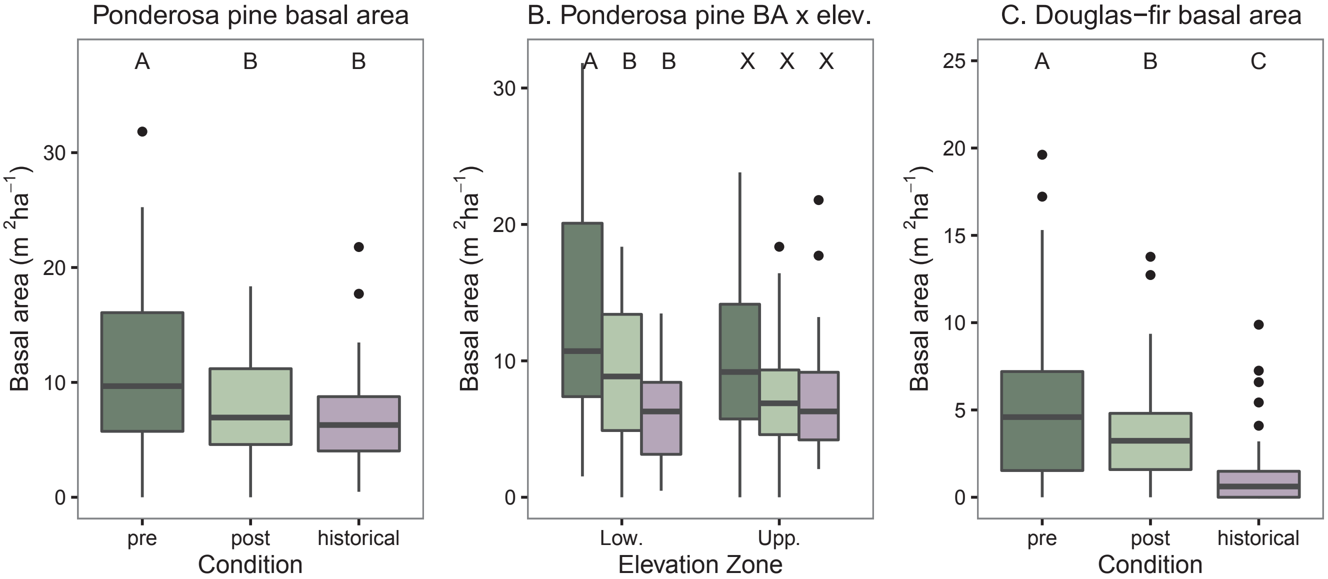

Fig. 5. Boxplots comparing pre- and post-treatment composition metrics to historical conditions, including (A) ponderosa pine basal area, (B) ponderosa pine basal area summarized by elevation zone, and (C) Douglas-fir basal area. Conditions not sharing a letter are significantly different (Tukey's honest significant difference, $p_{adj} < 0.05$). In panel B, *post hoc* Tukey's tests were conducted separately for elevation levels due to a significant interactive effect. See text for full details.

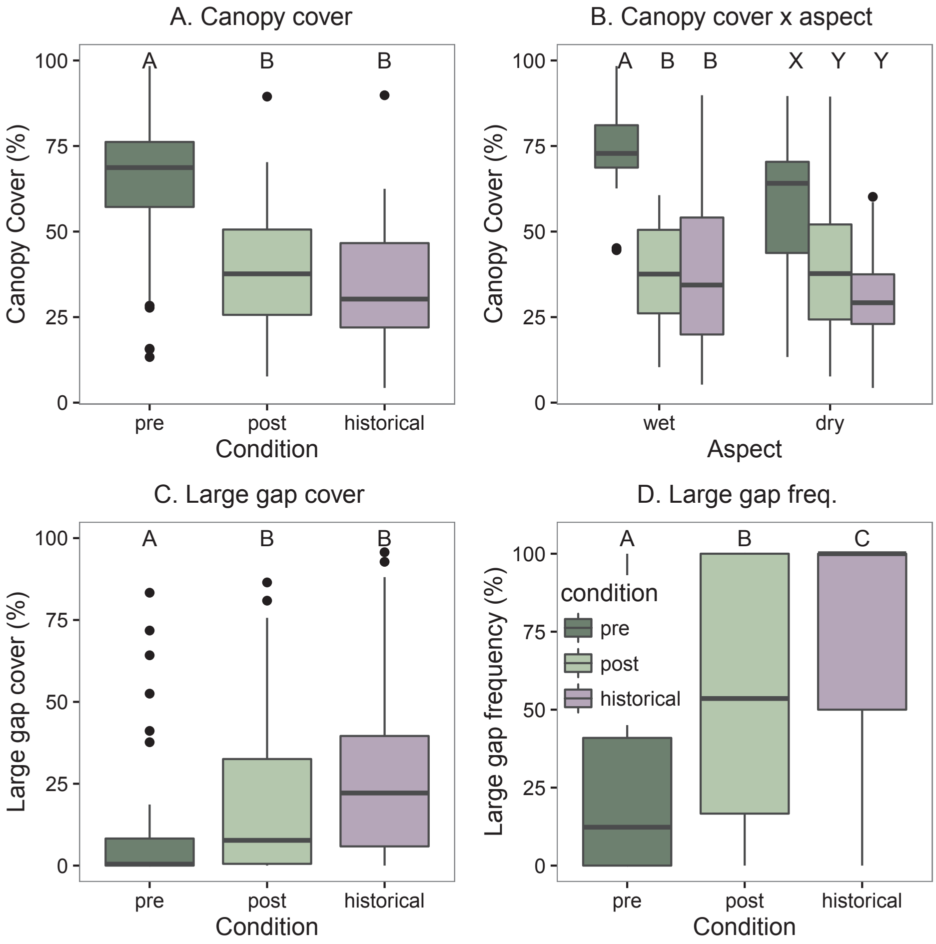

Fig. 6. (A) Boxplots comparing pre- and post-treatment canopy cover to historical conditions along with (B) comparisons of canopy cover summarized by aspect. Comparisons of pre- and post-treatment gap metrics to historical conditions are summarized for (C) coverage of large gaps and (D) frequency of large gaps. Conditions not sharing a letter are significantly different (Tukey's honest significant difference, $p_{adj} < 0.05$). In panel B, *post hoc* Tukey's tests were conducted separately for aspect due to a significant interactive effect. See text for full details.

generally overlap (Fig. 7D). These findings suggest that post-treatment stands have less variability in spatial patterns between wet and dry aspects as was historically present.

4. Discussion

4.1. Restoration of forest structure

Several restoration objectives of the LRI were met as early restoration treatments shifted aspects of forest structure in the direction of the desired conditions that the collaborative group identified (Addington et al., 2018; Dickinson and SHSFRR, 2014). Stand basal area was reduced by 35% following restoration treatments, and tree density was reduced over 50% (Fig. 4A and B). The goal to maintain higher tree density on wetter slopes relative to drier aspects was achieved, as post-treatment tree density was 40% higher on wet aspects relative to dry aspects (Fig. 4C). Although the desired condition to maintain higher tree density on wetter aspects was met, it should be noted that mean historical tree density was relatively similar across wet and dry sites. This suggests that desired conditions emphasizing variability in density and basal area across productivity gradients may need to be reexamined in light of historical data. A better understanding of how topographic factors like aspect drive forest structure and disturbance processes is an important consideration when framing desired forest conditions for restoration (Hessburg et al., 2015; North et al., 2009). Nevertheless, reductions in basal area and density from LRI treatments were similar to outcomes achieved in western US ponderosa pine forests, though considerable variation exists in treatment outcomes. For example, Fulé et al. (2012) report that typical basal area reductions following thinning treatments average approximately 30% and density reductions average approximately 50% among studies of western ponderosa pine- or Jeffrey pine (*Pinus jeffreyi* Balf.)-dominated forests. Ziegler et al. (2017) report basal area reductions of 43% and density reductions of 56% following seven restoration treatments across the Colorado Plateau and southern Rocky Mountains, including portions of treatment areas of the LRI. Such reductions in forest density likely reduce crown fire potential in treated stands (Agee and Skinner, 2005; Fulé et al., 2012; Ziegler et al., 2017).

Notwithstanding considerable reductions in forest density, some important differences persist between post-treatment and historical forest density. Most notably, mean post-treatment basal area and density remain substantially higher across all aspects and elevations compared to historical conditions (Fig. 4A), and differences in density were more pronounced on wet sites than dry sites (Fig. 4D). Post-treatment basal area and density were also greater than those resulting from low- and moderate-severity portions of wildfire affecting similar systems in the Front Range ($8\,m^2\,ha^{-1}$ and $179\,ha^{-1}$, respectively) which were instead strikingly similar to the mean historical conditions presented in this study (Malone et al., 2018). Deviations in post-treatment forest density from historical conditions were not unexpected given the constraints to LRI treatments discussed below and the very low average historical basal area ($8.3\,m^2\,ha^{-1}$) and tree density (158 trees ha^{-1}).

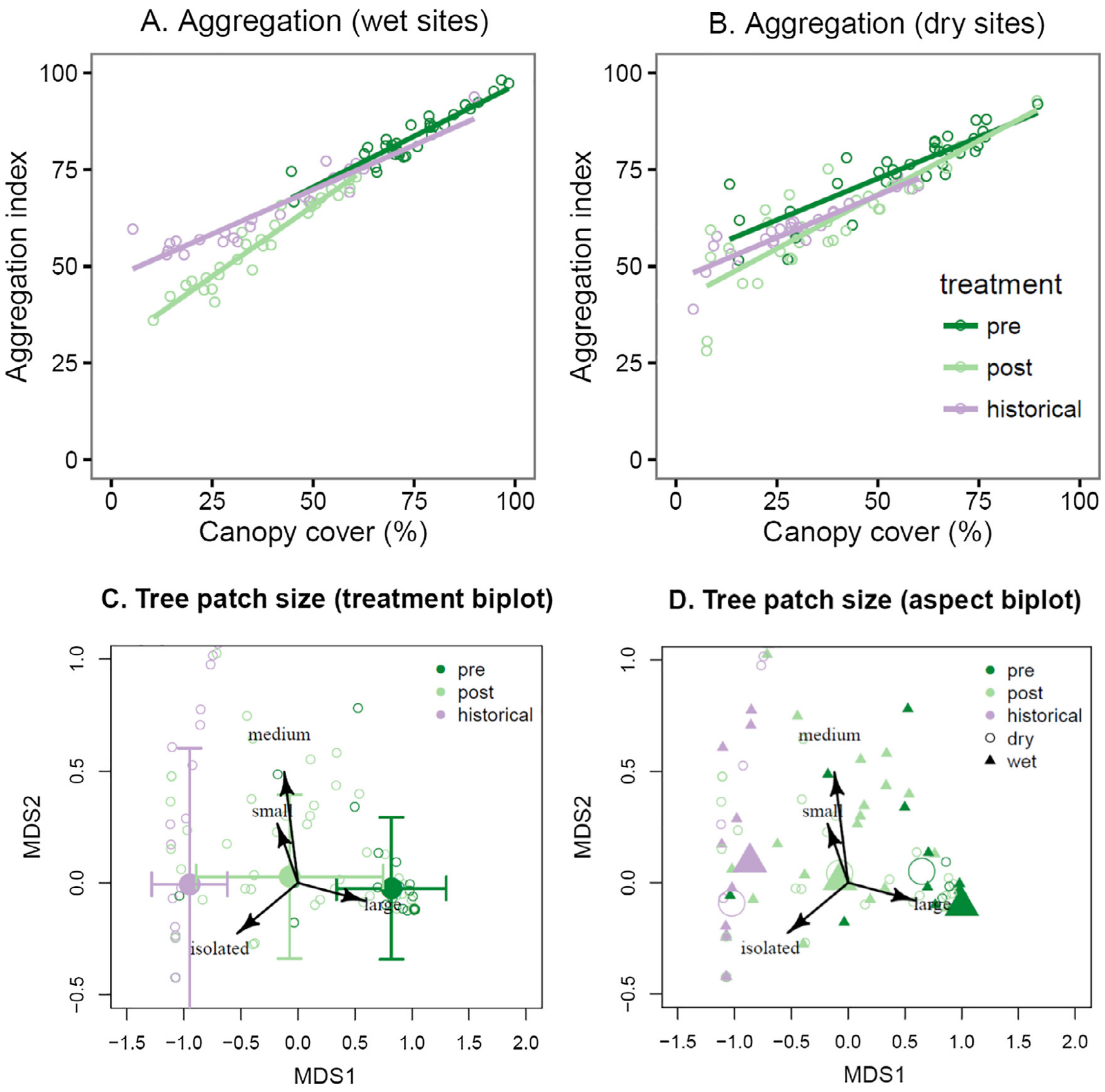

Fig. 7. (A–B) Aggregation index for pre- and post-treatment units and historical conditions as a function of canopy cover for (A) wet sites and (B) dry sites. (C–D) Non-metric multidimensional scaling ordination of tree patch size distribution in pre- and post-treatment sites compared to historical conditions. Length and direction of vector overlays indicate correlation of patch size abundances with ordination axes. (C) Filled circles represent means of ordination scores ± 1 s.d. of the mean axis score. (D) Mean condition scores summarized by aspect (wet vs. dry) to display variability among aspects within conditions. Large triangles represent mean axis scores for each combination of condition (pre/post/historical) and aspect (wet/dry).

However the early mechanical treatments of the LRI have forest density outcomes that resemble those achieved in other restoration efforts in ponderosa pine-dominated forests. Waltz et al. (2003) found that mechanical thinning and prescribed fire treatments decreased tree density and basal area to 2.5 and 6 times higher, respectively, than historical reference conditions in a ponderosa-pine and Gambel oak (*Quercus gambelii* Nutt.) forest in northwestern Arizona. Similarly, Mast et al. (1999) found that thinning and prescribed burning restoration treatments decreased tree density to 2.5 times higher than historical reference conditions in an unlogged ponderosa pine forest in central Arizona. Higher residual tree density may provide a buffer against tree mortality that may occur after harvest or subsequent prescribed fire and hedge against potential underestimation of reconstructed tree density (Battaglia et al., 2018b; Waltz et al. 2003). Allen et al. (2002) advocates for such a conservative approach to reducing fire hazard to matain future forest management options. However, additional stand entries may be required if further density reductions are ecologically desirable (Allen et al., 2002; Waltz et al., 2003).

The objective to favor ponderosa pine over other conifers was not accomplished in early restoration treatments despite that Douglas-fir removal was emphasized in all treatments. LRI treatments reduced the basal area of both ponderosa pine and Douglas-fir by approximately 28%. Waltz et al. (2003) report similarly modest changes in tree composition following restoration treatments where reductions in basal area were similar across ponderosa pine and other species. Ziegler et al. (2017) found relatively small changes in tree composition following restoration treatments aiming to increase spatial heterogeneity and promote ponderosa pine abundance. This shortcoming may be explained, in part, by LRI objectives which specify that higher residual densities and higher diversity be maintained on productive sites, which may lead to the higher than expected density we found on wet sites (Fig. 4C). Future treatments that place greater emphasis on removal of species such as Douglas-fir (especially on wet sites) may more successfully favor ponderosa pine and result in post-treatment tree composition more aligned with desired conditions.

Overall, substantial reductions in tree density led to reductions in canopy cover and increases in abundance of large gaps (> 18 m diameter), consistent with restoration goals. LRI treatments decreased canopy cover to 39% following restoration treatments bringing them into the higher range of historical estimates of mean canopy cover from other studies in the region (21% to 43%; Brown et al., 2015; Dickinson, 2014; Kaufmann et al., 2001). Further, we found that LRI treatments increased the abundance and cover of large gaps, making progress toward restoring historical fine-scale spatial patterns, and potentially restoring aspects of plant community structure driven by spatial patterns such as understory cover (Matonis and Binkley, 2018). However, differences in spatial patterns remain between post-treatment and historical conditions. We found that the frequency of large gaps was lower in post-treatment conditions than in historical conditions. The large gap cover was not significantly different between post-treatment (20%) and historical conditions (29%). Although the effect was not significant, the relative difference was rather large (–0.09/0.29 = –0.45), and large gap cover exhibits high variability relative to the other metrics, potentially masking lower large gap cover in post-treatment conditions, which may be detected if larger areas were sampled. Another potential explanation for differences in large gap frequency but not cover is that the spatial distribution of large gaps may differ at larger scales between restoration treatments and historical stands. Assuming similar density and size, large gap cover could be similar, but large gap frequency could be lower in restoration treatments if large gaps were highly concentrated in portions of some treatment units and absent in others. One limitation of this study is that the size of historical plots (0.5 ha) is small relatively to the scale of large gaps; thus, we are unable to examine how large gap size and frequency interactively determine total large gap cover. Future studies examining large gap characteristics of entire projects and their surrounding landscapes can facilitate comparisons with historical and modern reference conditions for large gap-size distributions (e.g., Dickinson, 2014; Malone et al. 2018).

Another goal of early LRI restoration treatments was to increase fine-scale tree spatial heterogeneity in accordance with historical conditions and restoration guidelines (Addington et al., 2018; Larson and Churchill, 2012; Reynolds et al., 2013). As expected, restoration treatments shifted the spatial pattern of trees away from dominance by large tree patches and toward greater diversity of tree patch size in accordance with treatment goals and historical conditions. Ordination analyses indicated that post-treatment stands were less dominated by large tree patches ($> 283\,m^2$) and instead contained more isolated trees and small- and medium-patches (Fig. 7C). Ziegler et al. (2017) found that restoration treatments generally reduced the abundance of large tree patches and in most cases increased tree aggregation. Although early restoration treatments created a more diverse mosaic of tree patch sizes, some spatial differences related to patch size distribution remain between post-treatment and historical stands. Historical stands contained a very low proportion of large tree patches (Fig. 7C) relative to current stands. Previous reconstructions within low-elevation ponderosa pine forests of the region suggest that approximately one-third of historical tree cover represented single (isolated) individuals and two-thirds of tree cover comprised tree groups (Brown et al., 2015). Our ordination analysis suggests that historical stands also contained a greater range of tree patch structures among plots (higher variability along NMS axis 2), and post-treatment aggregation of canopy patches was lower on wet aspects relative to historical patterns (Fig. 7A).

4.2. Constraints to adaptive management in large-scale forest restoration initiatives

One of the most striking differences highlighted by comparisons between LRI restoration treatment outcomes and historical conditions was the consistently high residual tree density relative to historical conditions. The comparisons presented in this study highlight several important scientific, social, and logistical constraints which may impact the CFLRP and other landscape-scale restoration initiatives. First, not all CFLRP programs of the western US have robust information on historical forest structure to serve as potential reference conditions for restoration efforts (Colavito, 2017). In the Colorado Front Range, detailed local information on historical forest structure were not available when desired conditions of the LRI were collaboratively developed. As a result, treatment objectives were expressed in general trends, rather than specific quantitative targets (Dickinson and SHSFRR, 2014). This approach provided the flexibility to balance other objectives during project design, but also produced a range of outcomes.

Second, legal and institutional constraints limited the extent to which collaborative restoration treatments can achieve the low density present in historical forests. Early LRI treatments necessarily occurred in areas already designated for active management in plans that preceded the LRI. The plans generally emphasized fuel reduction objectives rather than restoration to historical forest structure and thus did not permit basal area and density reductions necessary to approximate historical conditions. The ten-year scope of the CFLRP is relatively short compared to the length of time typical for approval and implementation of management actions on federal land. The challenge of integrating newly available scientific information (e.g., a systematic evaluation of historical conditions) into forest planning documents approved before the formation of the CFLRP has been identified as an obstacle to the effectiveness of collaborative restoration in CFLRP projects (Cheng et al., in review; Colavito, 2017). For example, in some LRI treatments, creation of large openings with mechanical treatments was restricted in pre-existing approved plans to < 0.1 ha, creating obstacles to achieving some LRI goals related to spatial variability. One way to alleviate this constraint is through active collaboration in not only individual restoration projects, but also in long-term treatment planning. A current effort of the LRI aspires toward such long-term collaborative planning (Upper Monument Creek Collaborative, 2016). Another constraint that has been recognized across several CFLRP programs is that although exchange of recommendations between stakeholders and implementers occurs through informal means such as annual meetings and field trips, there is limited evidence that stakeholder recommendations based on research and monitoring are successfully incorporated into planned and future projects through formal means (Cheng et al., in review). Within the LRI, forest management practices such as increased use of cut- or leave- tree marking as opposed to designation by prescription has been adopted to increase the congruence of restoration outcomes to LRI treatments (Underhill et al., 2014). However, establishing formal avenues of input from collaborative learning remains a challenge, but may facilitate achievement of desired conditions in landscape-scale restoration programs (Cheng et al., in review).

Third, topographic and logistical constraints limit both the methods and prescriptions appropriate for treatments in certain areas. Achieving low desired densities is only possible where ground-based logging operations are feasible and material can be removed from the treatment units. Manual thinning, for example, must be used on steep slopes inaccessible to mechanized equipment and creates challenges for removal of larger trees (e.g., 30–40 cm). Thus, significant density reductions for treatments that leave material on site result in high levels of surface fuels which is inconsistent with treatment objectives, leading to approximately 40% higher residual density in stands following manual treatments vs. mechanized treatments (Underhill et al., 2014).

Lastly, the use of prescribed fire remains challenging and partially restricted in Colorado (Hickenlooper, 2015, 2012). The location of many treatments near residential communities and proximity to structures and facilities on non-national forest lands can constrain access, treatment methods, and outcomes. Due to constraints on the use of prescribed fire, incorporation of landscape-scale planning of restoration and fuel reduction programs may be a critical tool to maximize benefits of large-scale fire hazard and restoration treatment programs (Jones et al., 2017; Scott et al., 2013; Thompson et al., 2016).

4.3. Management recommendations for collaborative restoration

Within the context of the scientific and social constraints outlined above, differences between historical and post-treatment forests as outlined in this study highlight potential areas of adjustment for future restoration treatments and management goals in the Colorado Front Range. Based on these comparisons, we conclude with several recommendations that may improve the effectiveness of restoration efforts. First, historical data are often examined to infer historical range of variability of forest structure and to inform restoration efforts (Aplet and Keeton, 1999; Keane et al., 2009; Mast et al., 1999; Moore et al., 1999; Romme et al., 2003; Veblen, 2003; Waltz et al., 2003). Given the importance of historical data for informing restoration goals and the increasing availability of detailed information on historical conditions, we recommend updating desired conditions in light of newly available historical data. Many of the desired conditions initially specified by the LRI were framed in qualitative terms (e.g., “establish a complex mosaic of forest density”, Clement and Brown, 2011; Dickinson and SHSFRR, 2014). However, more quantitative descriptions of desired conditions and expected variability in various forest types and topographic settings can be developed (e.g., Battaglia et al., 2018b) and provide valuable information for modifying treatment design and implementation. Incorporation of spatial heterogeneity metrics (e.g., specification of large gap size distributions and tree group distributions) into prescription and marking protocols, for example, can improve restoration outcomes (Larson and Churchill, 2012).

Consistent with desired conditions, we found that post-treatment tree density differed across productivity gradients. However, these differences contributed to high residual stand densities and were larger than differences in tree density across productivity gradients in historical forests. Thus, we recommend refinement of desired conditions based on historical data to ensure that objectives are congruent with historical reference conditions. Of course, use of historical data as strict references for restoration has limitations in light of expected changes in components of disturbance regimes (Westerling et al., 2006) and species distributions due to an increasingly warmer and drier climate (Malcolm et al., 2002; Rehfeldt et al., 2014). However, basing forest management on historical range of variability provides an objective foundation for planning, which can be augmented with other management goals and adjusted to reflect predictions of future climates (Keane et al., 2009). Because climate change is expected to impact species distributions, disturbance regimes, and ecological processes, conservation strategies should consider and incorporate these anticipated changes. However, the inherent uncertainty in the direction and rate of these changes has led some conservationists to argue for an approach to conservation that also includes continued implementation of retrospective approaches to conservation that incorporate historical range of variability (e.g., restoration towards reference conditions), as a method of spreading ecological risk across a large range of potential climatic and ecological outcomes (Aplet and McKinley, 2017).

Our comparison of LRI restoration outcomes to historical conditions highlights several areas where restoration treatments can be adjusted for the Colorado Front Range. In light of new historical reference conditions, we propose that future restoration treatments (1) further reduce tree density, especially on wet sites, (2) remove more Douglas-fir relative to ponderosa pine, and (3) emphasize tree removal in an aggregated manner to enhance the number and cover of large gaps, and (4) emphasize increase tree patch-size diversity and differentiation of spatial patterns across productivity gradients. Additional analysis of post-treatment data on forest structure are warranted to inform future recommendations. The recommendations above are based on outcomes of early LRI treatments implemented in the first three years of the program. Consistent discussions and site visits among Forest Service staff and collaborators throughout the LRI program may facilitate adaptive management such that the outcomes of recent or future LRI treatments may differ from early restoration treatments as new knowledge and insights from previous projects are incorporated into future projects (Underhill et al., 2014). More recent treatments will be implemented under new forest planning efforts, which allows the creation of large openings; thus, outcomes may be more consistent with desired and historical conditions. In addition, the current analyses focus on comparing the means of forest structural metrics. However, more in-depth analyses comparing variability in pre- and post-treatment stands to historical conditions will provide a more comprehensive view of outcomes with respect to the variability within and among restoration treatments and provide inference for larger-scale planning (Dickinson and SHSFRR, 2014). Ongoing discussions within diverse collaborative groups of scientists, stakeholders, conservationists, and forest management staff will help ensure that large-scale restoration initiatives continue to meet management and ecological objectives.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.foreco.2018.04.026.

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