

TECHNICAL ARTICLE

Have we been successful? Monitoring horizontal forest complexity for forest restoration projects

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Forest management today often seeks to restore ecological integrity and enhance human well-being by increasing forest complexity, resilience, and functionality. However, effective and financially expedient monitoring of forest complexity is challenging. In this study, we developed a practical and inexpensive technique to measure horizontal forest complexity. This monitoring method uses intuitively understandable data (imagery) and facilitates stakeholder participation in the adaptive management process within collaborative projects. We used this technique to determine if current restoration projects are successfully achieving their spatial restoration goals. We focused on the Colorado Front Range Landscape Restoration Initiative (CFRLRI) as a representative of the typical collaborative restoration projects underway in formerly fire-dependent dry conifer forests. The developed monitoring method is practical and cost-effective by using free aerial imagery to map, quantify, and analyze the distribution of canopy cover pre- and post-treatment. We found the CFRLRI has successfully reduced canopy cover (from 44 to 26% on average) and increased some aspects of horizontal forest complexity. The application of these monitoring techniques has allowed the CFRLRI collaborative group to objectively quantify changes to horizontal forest complexity, and has facilitated stakeholder communication about forest spatial patterns. These methods could be adapted for use by other similar forest restoration projects around the world by utilizing increasingly available satellite or aerial imagery.

Key words: adaptive management, forest restoration, monitoring, participatory forest management, spatial heterogeneity, structural complexity

Implications for Practice

- Increasing horizontal complexity is an important goal of forest management today; however, it is challenging to describe, quantify, and monitor.
- We develop and implement a practical and effective method for monitoring horizontal forest complexity using aerial imagery.
- Forest restoration treatments by the Colorado Forest Landscape Restoration Initiative decreased forest canopy cover and mean canopy patch size as desired. Treatments increased forest horizontal complexity in some ways (mean and range of distances among canopy patches increased) but not others (the range of canopy patch sizes decreased).
- These methods have improved stakeholder communication and may be adapted for use by other forest restoration projects.

Introduction

Forest management today often seeks to restore ecological integrity and enhance human well-being by increasing forest complexity, resilience (*sensu* Holling 1973), and functionality (Rietbergen-McCracken et al. 2007). Forest complexity is the heterogeneous distribution and diversity of elements of the forest's physical structure (Helms 1998; Franklin & Van Pelt 2004;

McElhinny et al. 2005). The rationale behind increasing forest complexity is that the diversity of forest structures present in a complex forest will have differential vulnerability and resistance to disturbances, and therefore provide some resistance to, or greater ability to recover from, a perturbation (O'Hara 2014). In addition, forest management projects are increasingly using participatory and adaptive management processes to foster diverse stakeholder support, reduce the likelihood of disputes and ultimately increase the chance for restoration success.

Implementing restoration projects with objectives that include increasing forest complexity and stakeholder collaboration have proven to be challenging. One of the many challenges faced by these restoration projects has been the

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design and application of effective and financially expedient monitoring of forest complexity. Monitoring is a vital component of the adaptive management processes, as it provides the required information for stakeholders to evaluate and learn from management activities (Clement & Brown 2011; Aplet et al. 2014). To be effective monitoring methods must provide timely, accurate information about the ecological outcomes of the projects. Restoration projects that include stakeholder participation in management also require monitoring methods that are transparent, cost-effective, and easily understood by nonexperts (Gustavson et al. 1999).

Monitoring forest complexity is challenging because it requires quantifying variation in diverse forest characteristics, some of which have not been traditionally measured in forestry. Historically, measurements used to monitor forest structure have assumed forest homogeneity by focusing on the average conditions of the forest. Although these average conditions may describe important aspects of forest's structure, they do not describe the diversity and heterogeneous distribution of forest elements in space. This focus on the average conditions was well suited to forest management in the past, as managers typically sought to maximize efficiency of timber production by growing crops of similar trees and using all available growing space, which resulted in homogeneous forest conditions (Putteman et al. 2009). However, with the shift in management objectives and an increasing focus on ecological restoration in many parts of the world, forest managers need novel methods for measuring the diversity of forest structures across space.

Recreating a mosaic of open and forested conditions is increasingly recognized as a restoration objective in formerly fire-dependent conifer forests that have been homogenized by intensive management and/or fire suppression. This is relevant to pine-dominated forests around the world, from ponderosa pine and mixed conifer forests in the western United States (Covington & Moore 1994) and Canada (Marcoux et al. 2015), northeastern U.S. pine barren systems (Bried et al. 2014), longleaf pine (*Pinus palustris* Mill.) forests of southeastern United States (Mitchell et al. 2006), and pine-dominated areas in Mediterranean Europe (Rodrigo et al. 1999; Pausas et al. 2004), central Asia (Hessl et al. 2012; Saladyga et al. 2013), the Middle East (Ne'eman 1997), and northern Africa (Moravec 1990). Restoration of these forests typically aims to increase canopy cover heterogeneity to emulate forest structures created by historical mixed-severity fire regimes by creating patchy forest cover with large openings, groups of trees, and isolated trees within each treatment unit (Covington & Moore 1994; Clement & Brown 2011; Larson & Churchill 2012; Dickinson et al. 2014). However, many techniques that can be used to describe horizontal spatial patterns require painstakingly mapping the location of all stems in the stand and calculating complex spatial statistics to characterize the pattern of trees (Ripley 1988; Pommerening 2002; Fortin & Dale 2005; McElhinny et al. 2005). Furthermore, these metrics tend to be abstract indices that are difficult to interpret by nonexperts, creating a barrier to stakeholder collaboration. The intensive nature of these approaches requires detailed measurements,

and are generally uneconomical for monitoring landscape-scale restoration projects with limited budgets.

Remote sensing techniques, such as those using Light Detection and Ranging (LiDAR) and multispectral aerial imagery (Campbell & Wynne 2011), can rapidly quantify forest spatial complexity over large areas. LiDAR is expensive, requires sophisticated analyses, can be challenging to interpret, and is currently limited in its availability, although it is becoming more widely available and may be an inexpensive data source for monitoring large areas in the future. In contrast, multispectral aerial imagery is currently collected regularly in many countries and is available at low cost. Furthermore, imagery is itself an excellent communication tool, as stakeholders can view and understand it with little explanation. Methods using aerial imagery show great promise for use in the monitoring of horizontal forest complexity for collaborative restoration projects as data are widely and frequently available.

Another challenge to effective monitoring is defining the appropriate spatial scale at which to measure horizontal complexity. The scale of interest strongly influences forest complexity. For example, forest managers may increase fine-grain forest complexity through variable thinning to create individual trees, clumps of trees and openings (Churchill et al. 2013) while homogenizing the forest at a coarser extent by creating a regularly repeating pattern. Furthermore, both restoration experts and nonexperts alike often have difficulty conceptualizing horizontal forest complexity across spatial scales, and communicating their preferred outcome for restoration. Desired conditions need to explicitly define the spatial scale of complexity to be created, and monitoring methods must match these spatial scales.

The objectives of this study were: (1) to develop a practical and financially expedient technique to measure horizontal forest complexity that would facilitate stakeholder participation in the adaptive management process; and (2) to use this technique to determine if restoration projects are successfully achieving spatial restoration goals. To achieve these objectives, we focused on the Colorado Front Range Landscape Restoration Initiative (CFRLRI), as a representative of collaborative restoration projects currently underway in the dry forests of the western United States. We hypothesized that restoration projects implemented by the CFRLRI have achieved their aims of reducing forest cover and increasing horizontal forest complexity at the treatment unit scale.

Methods

Study Area

The study area is situated within the 320,000 ha of Colorado's foothills of the Rocky Mountain's identified as in need of restoration by the CFRLRI (2010) (Fig. 1). The CFRLRI is a collaboration between the Pike-San Isabel National Forest, Arapaho-Roosevelt National Forest, and the Colorado Front Range Roundtable (<http://www.frontrangeroundtable.org>) and was formed to expedite forest restoration in the region. CFRLRI estimates that roughly 70% of the Front Range's lower

montane ponderosa pine (*Pinus ponderosa*)/Douglas-fir (*Pseudotsuga menziesii*) forests (approximately 1,800–2,400 masl) are in need of restoration due to the effects of historical grazing and logging, and fire suppression over the past century (Kaufmann et al. 2000; Veblen & Donnegan 2005; Sherriff & Veblen 2006). The CFRLRI aims to restore these forests by decreasing forest density, increasing the dominance of ponderosa pine, and increasing forest horizontal complexity (CFRLRI 2010; Clement & Brown 2011; Dickinson et al. 2014). Treatments include tree thinning using mechanized and manual harvesting methods, followed by product removal, lop-and-scatter, and/or pile-and-burn treatments. Since 2010, the work has been funded through the United States Forest Service Collaborative Forest Landscapes Restoration Program (CFLRP) to carry out these restoration treatments and monitor the outcomes of these treatments using a collaborative approach. Importantly, the CFRLRI has taken an adaptive management approach with the active participation of stakeholders. Specifically, we focused on the 3,800 ha of montane ponderosa pine forest that were treated by the CFRLRI between 2010 and 2013.

Restoration Objectives and Forest Structure Elements of Interest

Stakeholders in the CFRLRI are concerned changes in forest condition since Euro-American settlement have increased wild-fire hazard, reduced understory species diversity, and degraded wildlife habitat. The current dense closed canopy is a primary driver of all three concerns because it (1) increases fuel contiguity and allows for the propagation of severe wildfires across the landscape; (2) shades the understory reducing plant cover and species diversity; and (3) does not support wildlife species that prefer open or mixed forest conditions. Therefore, the collaborative chose to focus on quantifying and monitoring the distribution and heterogeneity of canopy cover (the vertical projection of the canopy onto the ground *sensu* Jennings et al. 1999) as a measure of forest complexity.

The collaborative group chose to focus on the stand (treatment unit) as the scale of interest for monitoring because it is the scale at which the restoration treatments are applied. While the treatments are planned within the context of the surrounding landscape, the outcomes of the treatments within each treatment unit may be used to inform future treatments through adaptive management. The CFRLRI is currently working to develop additional methods for monitoring landscape-scale forest complexity.

Data Collection

The National Agriculture Imagery Program (NAIP) collected aerial imagery for Colorado in 2009, 2011, and 2013. This image is free and includes four bands (red, green, blue, and infrared) with a 1-m ground sample distance. At a minimum, the horizontal accuracy of the imagery must be within 6 m and cloud cover must be less than 10% per quarter USGS topographic quadrangle tile.

Data Analysis

We quantified the spatial pattern of forest cover pre- and post-treatment in all units treated between 2010 and 2013 using the methods described by Pelz and Dickinson (2014). There were 129 individual treatment units, with a mean unit size of 28 ha. We used ENVI (Exelis Visual Information Solutions, Boulder, CO, U.S.A.) to classify canopy cover from the imagery. Before classification, we resampled the NAIP imagery to a 2.4-m resolution to reduce the influence of intra-canopy shadows (Meddens et al. 2011) and added an additional band by calculating the simple ratio (SR), the ratio of the near-infrared to red band. We performed a supervised classification of the imagery into four cover types (canopy cover, herbaceous ground cover, deep shade, and bare ground [including exposed soil, rock, and paved roads]) using the Mahalanobis distance algorithm with the five bands (red, green, blue, near-infrared, and SR). The calculated Jeffries–Matusita separability of all classified cover types was greater than 1.8 (Richards 1999). Classification was verified against an independent set of manually classified regions and the confusion matrix calculated. All classified images had a Kappa coefficient greater than 0.8 (Landis & Koch 1977) and classification accuracy greater than 0.8 for canopy cover.

The spatial patterns of canopy were analyzed using ArcGIS 10.2 (Environmental Systems Research Institute [ESRI], Redlands, CA, U.S.A.) and FRAGSTATS (McGarigal et al. 2012). We chose metrics to provide a full description of canopy patterns, including the prevalence, spatial distribution, size, and shape of canopy patches, with a preference for those that could be intuitively understood by nonexperts (Table 1). The stakeholders then established desirable trends as monitoring benchmarks using these metrics (Table 1). Desirable trends rather than target ranges were used as there is ongoing scientific debate about the historical range of forest conditions, and little consensus could be reached on specific targets. However, the stakeholders reached agreement on the desirable trends which could be used as a starting point for adaptive management.

To further corroborate the use of aerial image analysis to map the canopy, we compared the canopy cover quantified using aerial image analysis to field-measured canopy cover for a subset of five treatment units pre- and post-treatment ($n = 10$), with each observation treated as independent for the purposes of this analysis. The field-measured canopy cover was quantified by Briggs et al. (unpublished raw data) using between three and nine permanent 100 m intercept transects per treatment unit. The mean percent of transect length covered by canopy was calculated for each treatment unit, and simple linear regression was used to statistically compare the canopy cover quantified using aerial imagery (%) to the field-measured canopy cover (%). The mean treatment unit canopy cover was compared, as even small a mismatch in transect location between the two datasets would have a large impact on the canopy cover measurements and therefore influence the outcome of the comparison. Furthermore, direct comparisons transect-by-transect would be spurious, given the differences between the resolutions of the two datasets.

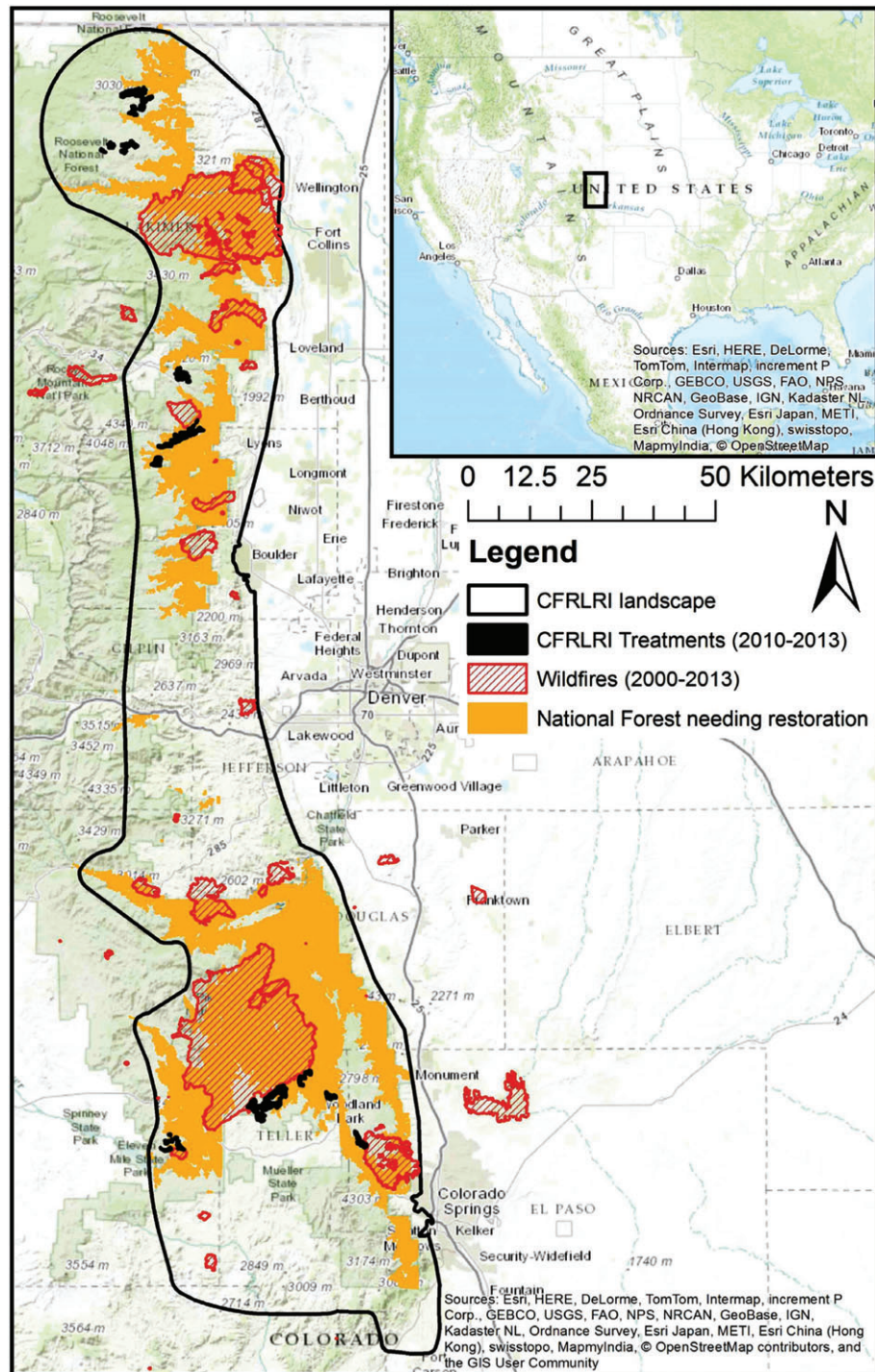


Figure 1. Map showing the location of the CFRLRI restoration treatments completed between 2010 and 2013. The boundaries of the CFRLRI landscape (approximately 6,000 km²) and reported wildfires between 2000 and 2013 are also shown.

We used a rank-transformed analysis of variance (ANOVA) to test for differences between pre- and post-treatment values ($\alpha=0.05$, $n=258$, one factor with two levels for pre- and post-treatment) because all metrics were found to be non-normally distributed (using a Shapiro–Wilk test; $\alpha=0.05$).

Results

Ground-collected canopy cover data from transects matched well with our remotely sensed aerial imagery analysis of canopy cover, indicating our methods had good accuracy at the treatment unit level. There was a statistically

Table 1. Metrics used for canopy cover analysis and their expected trend under successful restoration.

Metric	Definition and Units	Formula	Desirable Trend
PLAND	Area of each patch type as a percent of total landscape area (%) (McGarigal et al. 2012).	$P_i = \frac{\sum_{j=1}^n a_{ij}}{A} (100)$ P_i = proportion of landscape occupied by patch type (class) i . a_{ij} = area (m^2) of patch ij . A = total landscape area (m^2).	Decrease
LPI	The percentage of total landscape area comprised by the largest patch (%). It is a measure of the dominance of the largest patch of each patch type (McGarigal et al. 2012).	$LPI = \frac{\max_{j=1}^n (a_{ij})}{A} (100)$ a_{ij} = area (m^2) of patch ij . A = total landscape area (m^2).	Decrease
ED	The length of patch edge per unit area (m/ha) for each patch type. Edges are where adjacent patches influence each other are an important driver of ecological processes in complex landscapes (McGarigal et al. 2012).	$ED = \frac{\sum_{k=1}^m e_{ik}}{A}$ e_{ik} = total length (m) of edge in landscape involving patch type (class) i ; includes landscape boundary and background segments involving path type i . A = total landscape area (m^2).	Increase
PA	The size of a patch (ha) by type (McGarigal et al. 2012).	$AREA = a_{ij} \left(\frac{1}{10,000} \right)$ a_{ij} = area (m^2) of patch ij .	Decrease in mean. Maintain relatively high range and standard deviation
PARA	A ratio of the perimeter of a patch to its area (unitless). Large perimeter-to-area ratios indicate convoluted or complex edges with greater proportions of the area influenced by neighboring patches (McGarigal et al. 2012).	$PARA = \frac{P_{ij}}{a_{ij}}$ P_{ij} = perimeter (m) of patch ij . a_{ij} = area (m^2) of patch ij .	Increase
PD	Simple measure of the density of patches per 100 ha. Patch density is an indication of the prevalence of patch types (i.e. canopy or opening) and is strongly influenced by the size of patches (McGarigal et al. 2012).	$PD = \frac{n_i}{A} (10,000) (100)$ n_i = number of patches in the landscape of patch type (class) i . A = total landscape area (m^2).	Increase
ENN	The shortest straight-line distance between the focal patch (m) and its nearest neighbor of the same type. This simple measure of patch context is used to quantify patch isolation (McGarigal et al. 2012).	$ENN = h_{ij}$ h_{ij} = distance (m) from patch ij to nearest neighboring patch of the same type (class), based on patch edge-to-edge distance, computed from cell center to cell center.	Increase in mean, range, and standard deviation
ENRP distance	The shortest straight-line distance (m) between randomly generated points and the nearest contiguous patch of canopy. This is an indicator of the prevalence and size of gaps.	$ENRP = h_{ij}$ h_{ij} = distance (m) from a random point ij to nearest neighboring patch, based on patch edge-to-edge distance, computed from cell center to cell center.	Increase in mean, range, and standard deviation

significant relationship between the field-measured and aerial image analysis canopy cover ($p < 0.001$, Fig. 2). The coefficient of determination was large ($R^2 = 0.82$), indicating that a large proportion of variance in field-measured canopy cover can be predicted aerial image analysis. However, it should be noted that the aerial image analysis under-predicted the canopy cover in comparison with the field measurements. These differences may be attributed to the measurement resolution of the two approaches. For example, the field-measured transects were measured to the nearest 0.1 m, whereas the aerial imagery had a resolution of 2.4 m for the aerial imagery. In addition, the field-measured transects are a one-dimensional measurement (i.e. transect length), compared with

a two-dimensional measurement of canopy cover using the aerial imagery (i.e. area).

The restoration treatments reduced forest canopy cover and increased openness of these forest stands, as desired (Table 1 and Fig. 3). The percent of the area covered by forest canopy (PLAND) decreased by 17.8% on average, from 43.6 to 25.8% ($p < 0.001$). In addition, the density of patches (PD) increased by 15%, from 2,518 to 2,902 patches per 100 ha ($p = 0.008$). Before treatment, the single largest canopy patch (LPI) occupied 21.8% of the treatment unit's area, on average, whereas post-treatment average LPI was reduced to just 6.5% ($p < 0.001$). Likewise, the mean patch area (AREA) was reduced from 0.051 ha to just 0.011 ha ($p < 0.001$). Patches are also more isolated following

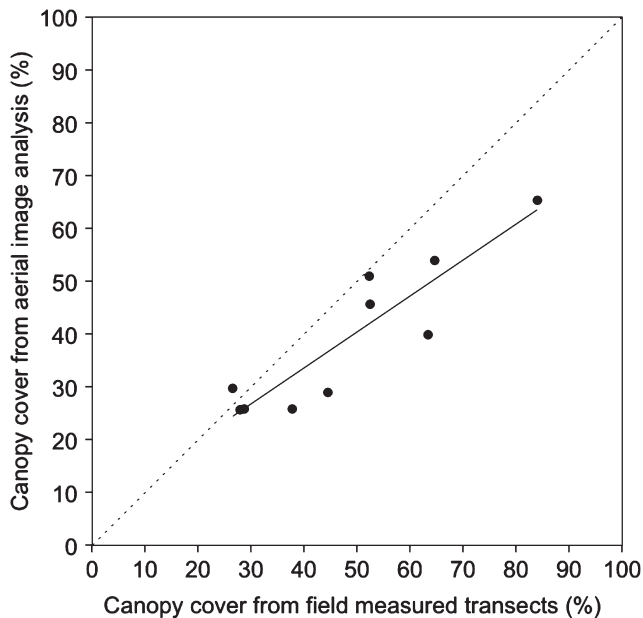


Figure 2. The canopy cover quantified using field-measured intercept transects corroborates measurements of canopy cover from aerial image analysis. Each filled circle is the canopy cover of a treatment unit either pre- or post-treatment. The solid line is the line of best-fit using simple linear regression ($\text{CanopyCover}_{\text{AerialImage}} = 0.6803 \text{ CanopyCover}_{\text{Transect}} + 6.4027$; $p < 0.001$; $R^2 = 0.82$). The dotted line is the line of perfect correlation.

treatment. The mean Euclidean distance between nearest neighbors (ENN) increased from 5.4 to 6.3 m, and the mean Euclidean distance between random points and their nearest neighboring patch (ENRP) increased from 2.3 to 4.6 m (both $p < 0.001$).

The treatments increased the variation of distances among canopy patches, suggesting that the forest stands in some ways became more heterogeneous following treatment, as desired (Table 1). The ENN range increased from 10.4 to 17.8 m ($p < 0.001$) and the ENN standard deviation increased from 1.2 to 2.5 m ($p < 0.001$). Likewise, the ENRP range increased from 14.2 to 25.7 m ($p < 0.001$) and the ENRP standard deviation increased from 1.9 to 4.0 m ($p < 0.001$). Therefore, while the treatments only increased the mean spacing among canopy patches by approximately 2 m, the variation in these distances approximately doubled.

Three metrics of forest complexity had trends counter to those expected under successful restoration (Table S1, Supporting Information). There were significant reductions in the range of canopy patch sizes within the treatment units (from 6.3 to 1.5 ha; $p < 0.001$), the standard deviation of patch sizes within the treatment units (from 0.36 to 0.07 ha; $p < 0.001$), and the mean perimeter–area ratio (PARA, from 12,043 to 11,859 m/ha; $p = 0.0152$). The distribution of canopy patches within the treatment units demonstrated a strongly “reverse-J” shaped distribution with many small canopy patches and few large patches (Fig. 4). The decrease in the mean, range, and standard deviation of patch sizes within the treatment units reflect the removal of large canopy patches, as demonstrated in Figure 4.

Furthermore, there was no significant differences between pre- and post-treatment in terms of canopy patch edge density (ED, $p = 0.570$, Table S1).

Discussion

We developed a practical and inexpensive technique to measure horizontal forest complexity for the monitoring of collaborative forest restoration projects, and used it to evaluate if restoration projects are moving forests toward the desired spatial pattern. The CFRLRI, as a representative of collaborative restoration projects underway in the dry forests of the western United States, is achieving the many of their horizontal forest complexity objectives.

The treatments successfully reduced the canopy cover to 25.8%, and these stands are now likely to be within range of historical canopy cover (Fornwalt et al. 2002). Fornwalt et al. (2002) used reconstruction methods to estimate that the historic canopy cover of a 4-km² landscape near Cheesman Lake on Colorado’s Front Range ranged between 13 and 22%. Furthermore, by reducing the amount and continuity of canopy throughout treatment areas and increasing horizontal forest complexity, the CFLRI has likely reduced the potential spread of crown fire within treatment units in all but the most extreme weather conditions (Agee & Skinner 2005; Fulé et al. 2012), but much of this effect may also be contingent on surface fuel treatment (Stephens et al. 2009; Safford et al. 2012). Our results demonstrate that, prior to treatment, the canopy cover of these stands was extensive, with the single largest canopy patch covering 22% of treatment units. Under these conditions, a crown fire may be likely to spread throughout the contiguous canopy and could cause high mortality under even moderate weather conditions (Agee & Skinner 2005; Fulé et al. 2012). Following treatment, the average single largest patch of canopy in each unit was reduced to just 7%, canopy patches were further apart, and the distance among canopy patches was more variable, suggesting that a fire that occurred now may have more localized and heterogeneous effects than if it occurred before treatment (Agee & Skinner 2005; Fulé et al. 2012).

However, not all of the indices indicated increased horizontal complexity, in part because stands were, in some ways, complex prior to treatment. Specifically, canopy patch size was highly variable prior to treatment. Unsurprisingly, the treatments reduced the diversity in canopy patch sizes. The largest patch influences the diversity of canopy patch sizes and breaking-up the canopy will reduce the complexity of the stand as measured variation in patch size. Furthermore, the reduction in the perimeter–area ratio suggests that the prevalence of canopy edges has been reduced, indicating increased homogeneity. These results concur with other studies that detected high levels of forest complexity prior to treatment (Cadry 2014; Ziegler 2014). In stands with diverse canopy patch sizes prior to treatment, restoration should aim to retain a full range of canopy patch sizes while decreasing total canopy cover.

The CFRLRI have adopted these monitoring methods for implementation alongside traditional forest inventories, wildlife

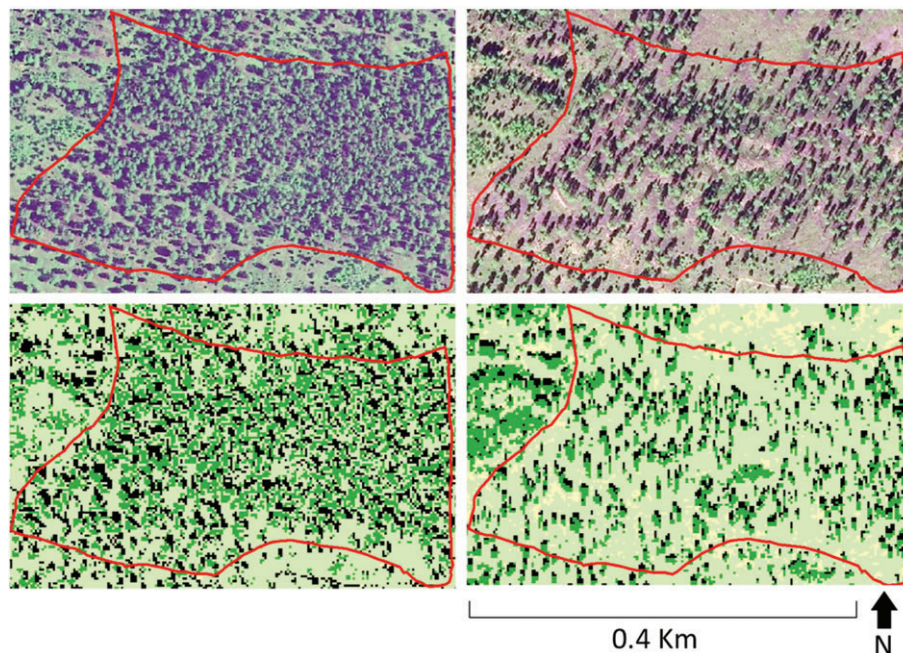


Figure 3. Example of pre- and post-treatment aerial imagery and classified images: Ryan Quinlan, Unit 10. Pre-treatment on the left, and post-treatment on right. The raw aerial imagery at the top and classified image at bottom. Red line indicates the unit boundary. In the classified images, dark green is forest canopy, black is shadow, and light green and yellow are ground vegetation and bare ground.

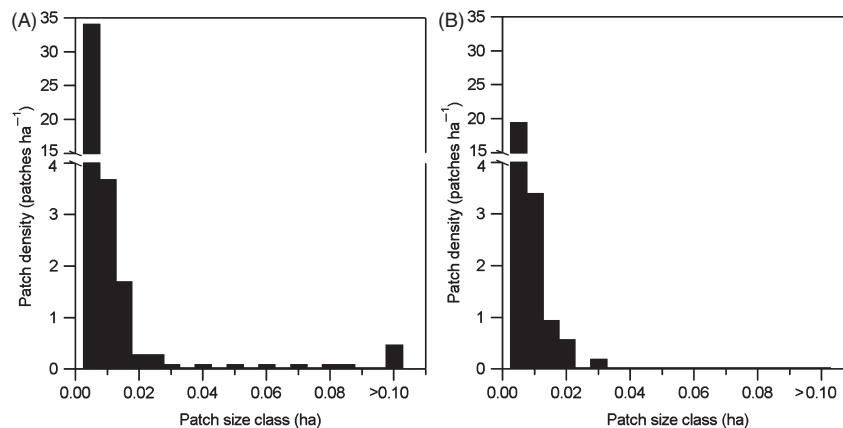


Figure 4. Distribution of canopy patch sizes pre- (A) and post-treatment (B) for Catamount Treatment Unit 2, as an example of the typical changes observed. The mean canopy patch size was reduced from 0.008 to 0.003 ha, and the range and standard deviation were reduced from 0.878 to 0.028 ha, and from 0.051 to 0.04, respectively. Please note the strong “reverse-J” distribution of patch sizes prior to treatment with a small number of large canopy patches (>0.04 ha). Post-treatment, all of these large canopy patches were removed.

monitoring, and monitoring of the understory plant community. The aerial imagery and analyses presented have been shared with the collaborative group, and incorporated into their adaptive management process (Aplet et al. 2014). Anecdotally, these monitoring methods have helped the collaborative to objectively quantify forest complexity and may improve the effectiveness of the adaptive management process. Prior to the development of these methods, stakeholders struggled to find the appropriate language to communicate patterns of horizontal forest complexity, often resulting in misunderstandings between stakeholders regarding their preferences.

The use of aerial imagery and their analyses have aided stakeholder communication by providing vocabulary and metrics to describe forest complexity within treatment units, though challenges in communicating, and defining, desired spatial characteristics certainly remain. In addition to canopy cover, the creation of openings is also of interest to the collaborative group (CFRLRI 2010; Dickinson et al. 2014). The Euclidean Nearest Random Point Distance (ENRP) metric used in this study is a measure of the stand openness, akin to empty-space metrics used to analyze point patterns (Ripley 1988). However, this metric does not directly measure opening size, shape, or

number. The collaborative is currently working on directly measuring openings as well as canopy cover by conducting FRAGSTATS spatial pattern analysis on the areas classified as openings rather than the canopy. The collaborative is also building on the lessons learned from stand-scale aerial image analysis to monitor treatment effects across the landscape.

Although the decision to monitor changes in canopy cover was well supported by the management objectives and members of the collaborative, all monitoring approaches have shortcomings that must be considered. Further work is needed to link these metrics to ecosystem processes and services. While canopy openness is linked to reductions in the spread of crown fires (Agee & Skinner 2005), these monitoring techniques do not quantify changes in surface fuels. Reductions in both canopy and surface fuels are necessary to substantially reduce overstory tree mortality from wildfires (Evans et al. 2011; Safford et al. 2012). Future monitoring of surface fuels will be essential to gauge if fire hazard or severity objectives are met. Furthermore, these metrics of horizontal complexity could be linked directly to other management objectives such as wildlife and understory plant habitat.

Comparing canopy cover spatial pattern to spatial patterns measured with different methods is an obstacle to using this method to inform restoration. In this study, comparisons of total canopy cover from aerial image analysis were strongly correlated with, but underestimated canopy cover from the field-measured transects. In addition, other published work addressing the distribution of forest cover, particularly focusing on historical conditions of western U.S. forests and efforts to restore these forest to their past conditions, has focused primarily on the arrangement of tree boles rather than canopy (e.g. Abella & Denton 2009; Sánchez Meador et al. 2011; Larson & Churchill 2012). Furthermore, restoration prescriptions usually rely on tree bole characteristics, not canopy cover (Churchill et al. 2013). It is not possible to locate the bole of each individual tree using aerial imagery, and therefore we were unable to create stem maps of the treatment units. However, DBH-to-crown allometry can be used to estimate historical canopy cover and horizontal complexity based on stem maps, allowing stem maps to be roughly translated to our canopy cover measurements. In addition, silviculturists commonly use allometric relationships to prescribe the number and size of residual trees required to achieve specified canopy cover for shelterwood treatments in other forest types (e.g. Leak & Tubbs 1983), and these prescription methods could be adapted to achieve canopy patches of specific sizes. Further work to translate stem-map spatial patterns to canopy cover patterns, or directly compare canopy cover patterns measured using different techniques, would help clarify restoration goals and would potentially improve restoration outcomes.

Although these methods are easily repeatable by nonexperts with basic geographic information system (GIS) and remote sensing skills using free data, this technique presents some challenges. Shadows may prevent the identification of canopy in localized areas, such as on steep shaded slopes or on the shaded side of tall trees, and therefore introduce errors into the quantification of the horizontal forest complexity. We attempted

to reduce the influence of small within-canopy shadows by decreasing the image resolution to 2.4 m, as this was found optimal size by Meddens et al. (2011). However, this coarser resolution probably contributes to the underestimation of percent canopy cover using the aerial image analysis in comparison to the field-measured transects. The accuracy of the supervised image classification was also ensured by only using training datasets with Jefferies–Matusita separability coefficients greater than 1.8 (Richards 1999), and classifications with overall Kappa coefficients (Landis & Koch 1977) and canopy cover classification accuracies greater than 0.8. If LiDAR data becomes more attainable and economical, it would allow for accurate canopy and opening classification without shadows. However, while the mapping and analysis of canopy cover using aerial photos did not produce perfect results, these methods provide a level of spatially explicit canopy cover data that is not feasible to obtain using field-based measurements.

The application of this practical, inexpensive, and transparent method to measure horizontal forest complexity has been shown to be effective in the context of monitoring a collaborative forest restoration project. It has allowed us to show that the CFRLRI has successfully reduced canopy cover and increased many aspects of horizontal forest complexity. The use of aerial imagery and associated metrics has improved stakeholder communication regarding horizontal forest complexity, and is facilitating adaptive management. There are a number of collaborative forest restoration projects throughout the western United States that aim to reduce hazardous fuels while modifying the horizontal complexity of coniferous forests that could use these methods to inform adaptive management. Furthermore, these methods could be customized to use other multispectral imagery sources. We hope that other collaborative groups working to increase horizontal forest complexity globally will be able to use these methods to quantify, and improve, their own restoration activities.

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Supporting Information

The following information may be found in the online version of this article:

Table S1. Summary of ANOVA tests comparing stand-scale pre- and post-treatment metrics.

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