

Application of tools for modeling stand-level restoration effects on landscape-scale heterogeneity

Pilot study for Jefferson County Open Space



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Introduction

Dry conifer forests of the western U.S. have endured many anthropogenic pressures including grazing, logging, and fire suppression that have led to stark increases in forest density [1,2]. In ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson) forests of the Colorado Front Range, these changes have contributed to uncharacteristic wildfires that threaten life, property, and forest and watershed health [3–5]. As a result, land management agencies are considering ways to address the problem of extensive fire hazard at meaningful scales. Often, mechanical treatments are used to reduce forest density and alter fuel structure to reduce the potential for high severity wildfire [6,7]. In addition to mitigating wildfire risk, restoration treatments in ponderosa pine emphasize restoring the high level of spatial variability that historically characterized these stands [8–10]. Guidelines for restoration in conifer forests emphasize that restoration treatments should increase spatial variability of overstory structure at both fine and coarse scales [11–13]. Complex forest structure at multiple scales can enhance resilience to disturbances like fire and drought, increase understory density, and improve wildlife habitat [10,11,14].

At fine scales, overstory spatial pattern is often described in terms of distributions of trees in various group sizes (individuals and clumps) (Figure 1A). Guidelines exist for historic distribution of tree groups for various regions and forest types [9,15], and tools such as visualization guides [16] and mobile applications [17] can aid in determining desired number of individual trees and groups of trees to ensure that tree marking during restoration treatments achieves fine-scale variability. However, restoration guidelines also emphasize variability at coarser

scales and emphasize maintaining variability across topographic features (Figure 1B). For example, restoration guidelines often prescribe variable overstory retention across wet and dry slopes, increasing variability in the size and structure of canopy openings, and maintaining variations in tree group size distributions across productivity gradients [12,13,18]. Incorporating coarse-scale variability into restoration treatments is challenging as it requires consideration of variables beyond an individual stand or land parcel under consideration, such as variability of topography and forest structure in the surrounding landscape. For example, prescriptions to change mean gap size and structure must consider how treatments in a particular management area contribute to larger landscape-scale desired conditions for gap structure. However, few tools are available to provide information on how individual forest treatments can contribute to landscape heterogeneity.

Simulations of forest management are often used to provide guidance to achieve landscape scale goals such as addressing fire risk to forests and watersheds, and achieving wildlife objectives [19–22]. These tools may also be useful for providing information on how management decisions influence landscape heterogeneity. The objectives of this study are to use a landscape-scale approach to evaluate how restoration at small scales can improve landscape-scale forest heterogeneity. Using two management units maintained by Jefferson County Open Space (JCOS), this approach simulates desired forest conditions at watershed scales (i.e., 1,000s to 10,000s of ha), to evaluate how conservation actions at finer scales (i.e., 100s to 1,000s of ha) contribute to coarser-scale benefits in forest heterogeneity. These analyses aid in conservation

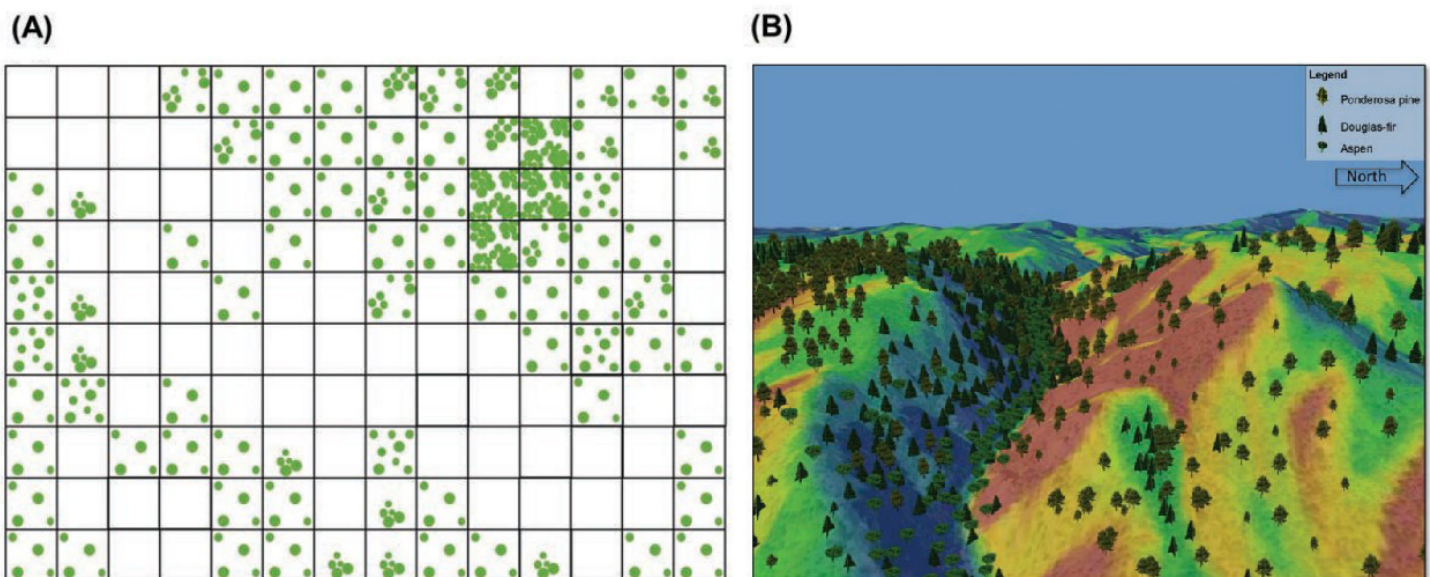


Figure 1. (A) Conceptualization of fine-scale variability in ponderosa pine forests with open stand structure illustrating composition of individual trees and tree groups of various sizes. (B) Illustration of physiographic influence on variability in stand density demonstrating increased density and tree group aggregation in wetter, sheltered aspects, and lower density and aggregation in drier, exposed aspects. Figure from Addington et al. 2018 [12].

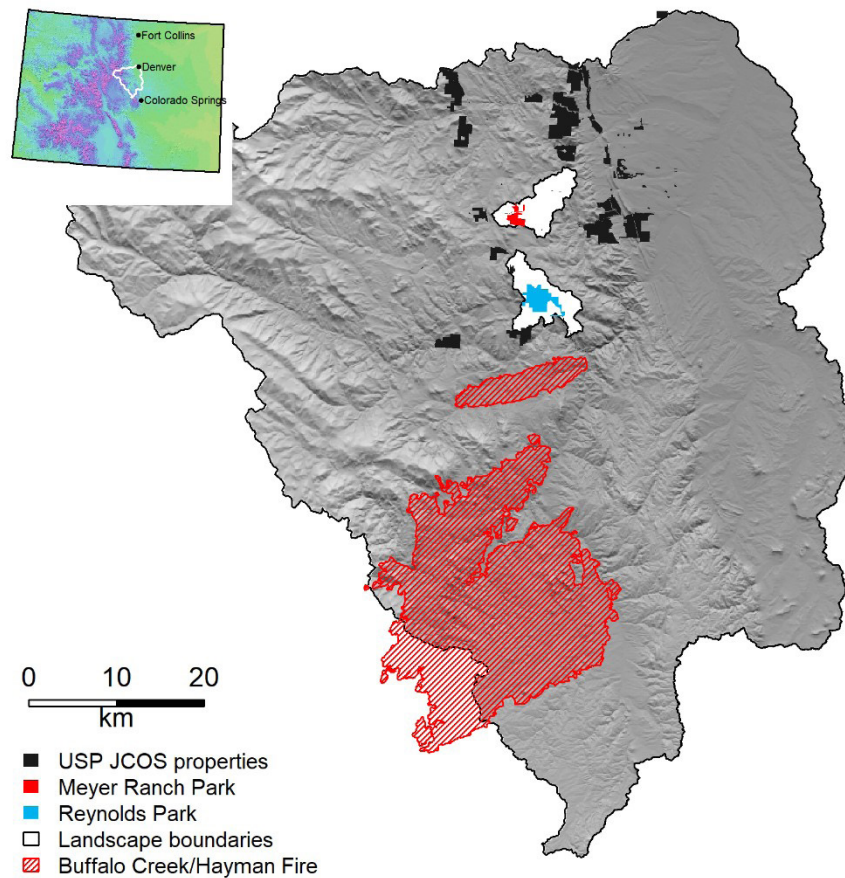


Figure 2. Study sites (solid red and blue polygons) and study landscapes (white polygons), along with Jefferson County Open Space (JCOS) properties within the Upper South Platte watershed in central Colorado. Red hashing denotes the Buffalo Creek fire (1996, upper), and Hayman fire (2002, lower).

prioritization and can be useful for assessing potential benefits of various proposed treatment locations.

Methods

Overall approach

The Upper South Platte (USP) watershed is a major water supply to Denver, CO and has seen substantial impacts from two major destructive fires leading to impactful post-fire erosion in recent decades (Figure 2) [4]. With its combination of extensive dense forests, fire hazard, erodible soils, and importance to metropolitan water supplies, this watershed has seen substantial investment in fire mitigation and restoration treatments in recent years with the aim of reducing the potential impacts of future wildfires [22,23]. The overall approach of this study is to use spatial data on existing forest structure to simulate a spatially heterogeneous restoration treatment based on historical forest structure. The simulation algorithm produces output landscapes that mimic historical canopy cover and variability at the landscape scale (e.g., 500 – 1000 ha). By comparing forest heterogeneity for untreated landscapes and landscapes with focal areas treated,

inferences can be made about how individual treatments can contribute to landscape-scale desired conditions.

To demonstrate the utility of landscape-scale analyses to inform stand-scale forest management, this report focuses on two forested units within the USP watershed managed by Jefferson County Open Space—Meyer Ranch Park (MRP) and Reynolds Park (RP). Both of these areas are currently under consideration for receiving forest restoration treatments. MRP is a 270 ha (667 ac) site in an upper montane mixed conifer forest with a mean elevation of 2516 m (8255 ft) and a mean slope of 12% ranging up to 28% [24]. RP is an 827 ha (2044 ac) lower montane ponderosa pine and mixed conifer forest site with a mean elevation of 2310 m (7578 ft) and a mean slope of 19% ranging up to 41% [24]. For each study site, this analysis delineated a larger study landscape (Figure 2) including all hydrological units adjacent to the treatment as defined by the National Hydrologic Dataset Plus [NHDPlus; 25]. These larger, landscape study areas were 3425 ha (8463 ac) and 4123 ha (10,180 ac) for MRP and RP, respectively.

Restoration simulation

Nationally consistent data on current forest structure

and composition are available from the Landfire program (30 m resolution raster) [24]. Effects of management practices on forest structure can be modeled by adjusting these data to simulate landscape-scale restoration and then simulating various ecological processes within modeled restoration projects [26]. Similar approaches have been used to explore landscape-scale impacts of management practices on fire behavior and risk, smoke production, and wildlife habitat [19,20,27].

To simulate the effects of restoration treatments aimed at restoring historic levels of canopy cover and variability, this analysis used a restoration simulation algorithm for each study landscape. First, the analysis defines desired forest structure for the simulation based on historical reconstructions of forest structure available for the region [2, Battaglia et al. unpublished data]. Preliminary analysis of these data led to selection of target conditions of 29% canopy cover (15% s.d.) within wetter, upper montane forests; 20% cover (8% s.d.) within drier upper montane forests; 20% cover (11% s.d.) within wetter, lower montane forests, and 17% cover (11% s.d.) within drier lower montane forests for demonstration. Second, each NHDPlus catchment was classified by climatic zone (upper montane or lower montane). Using a topographic wetness index [28], each catchment was divided into wetter and drier regions based on whether they had a topographic wetness index greater than (wetter) or less than or equal to (drier) a median value of 6.4 (Figure 3, top). Within each catchment, and within each moisture class, a potential distribution of canopy cover was generated based on the desired conditions by generating a vector of canopy cover distribution with a length equal to the number of pixels in each catchment using the betadist function in R [29]. Next, the canopy cover distribution vector and the topographic wetness index values were ranked, and canopy cover was assigned to each pixel in the catchment by matching ranks. Effectively, this process assigns the lowest canopy cover to the driest regions and the highest canopy cover to the wettest regions based on topographic wetness index, (Figure 3, middle). Simulations were constrained to only allow removal of cover to achieve desired conditions and not add canopy cover. Resulting simulations for each catchment and moisture class were merged to form a “fully restored” landscape raster for each site. The output from the untreated landscape and the treated landscape were merged within the study site boundaries to generate a simulation of restoration treatments within JCOS property boundaries. The untreated raster represents the current condition according to Landfire (Figure 4, left panels). The treated raster represents a restoration treatment occurring within the boundaries of the site with the goal of improving landscape-scale conditions (Figure 4, right panels).

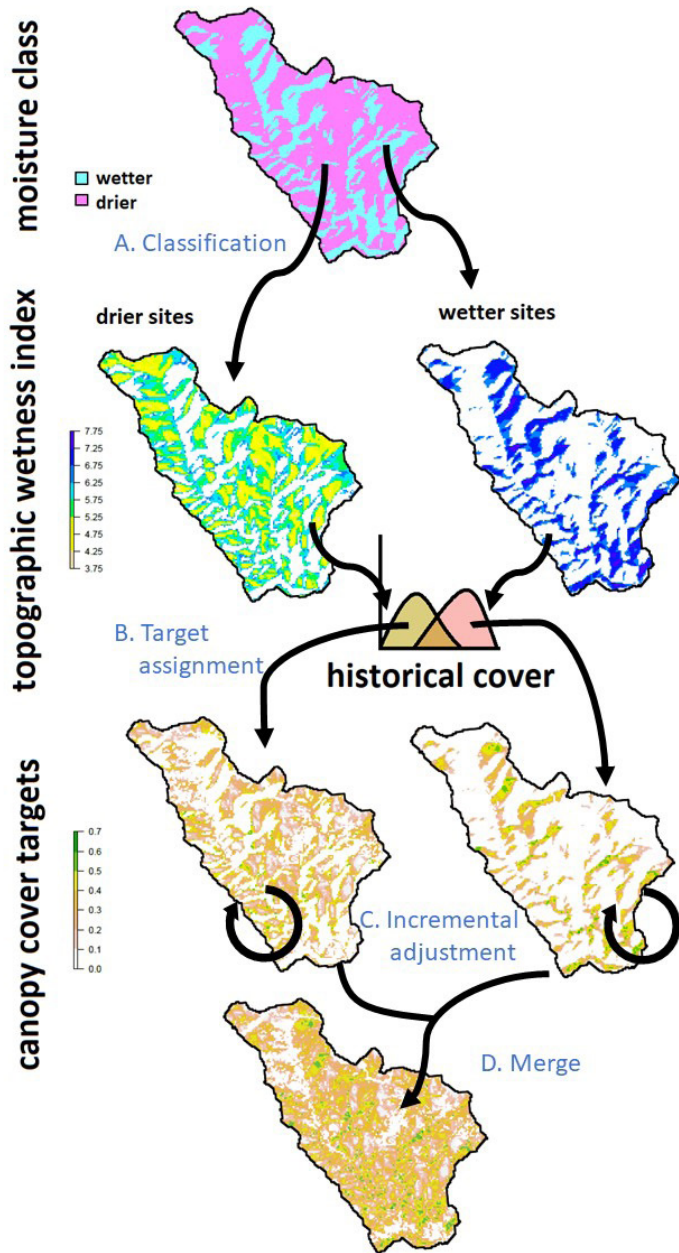


Figure 3. Schematic representation of restoration simulation algorithm which classifies each catchment into wetter or drier sites based on topographic wetness index (top), draws from historical distribution of canopy cover to assign desired canopy cover based on topographic wetness index for wetter and drier sites (center), and merges these outputs into a final restored landscape (bottom).

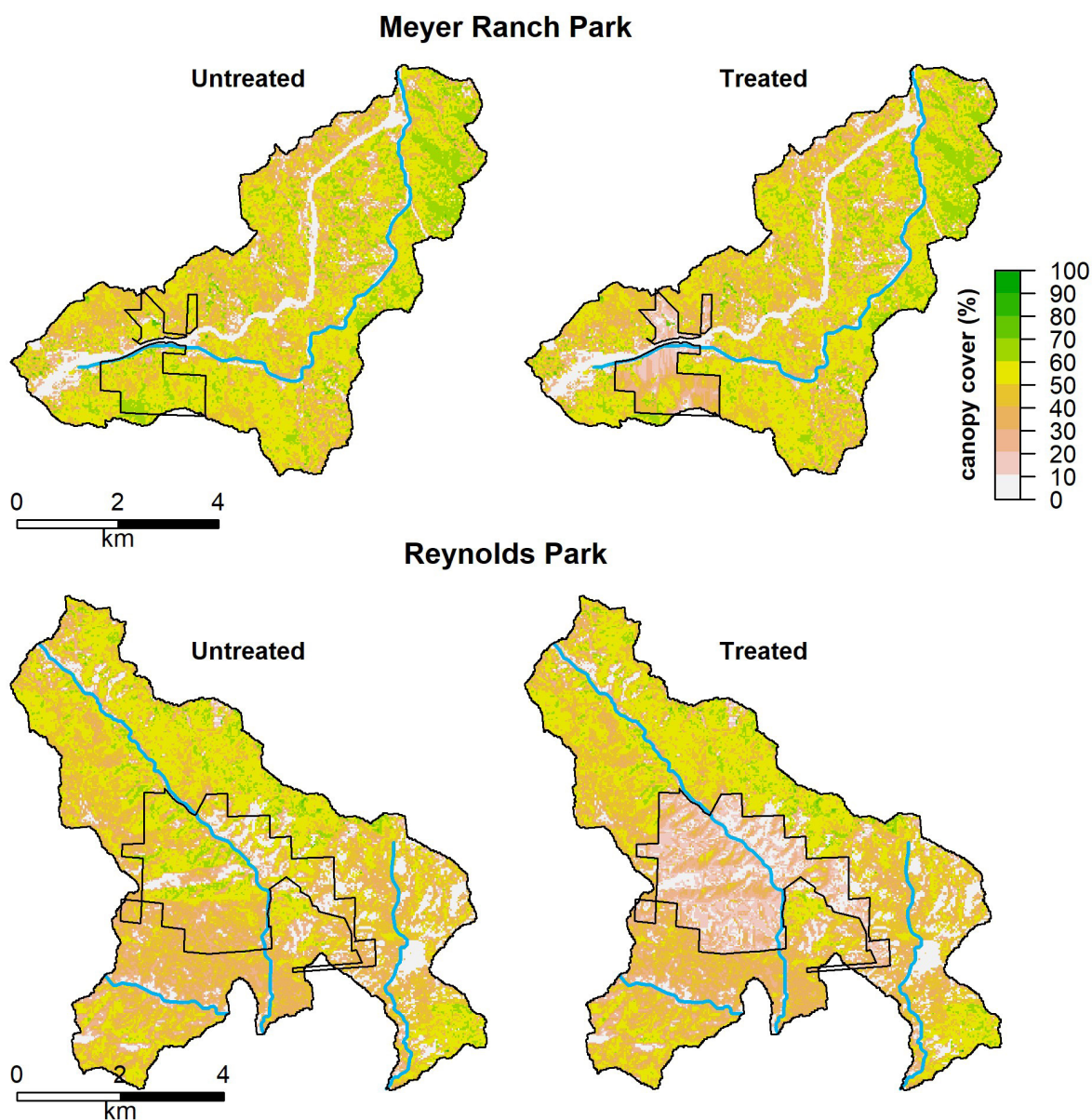


Figure 4. Restoration simulation outputs comparing the untreated and treated landscapes for Meyer Ranch Park and Reynolds Park study areas.

Landscape heterogeneity analysis

To assess changes in overall forest structure within simulated treatment area, several metrics indicative of changes in forest structure and heterogeneity were analyzed including mean canopy cover, and the coefficient of variation (c.v.) in canopy cover. To assess changes in gap structure, gaps were delineated as all areas with <10% cover with a minimum dimension of 60 m (approximately 0.3 ha, 0.75 ac) and metrics including gap cover, gap density, and mean gap size were calculated. To quantify changes in landscape diversity, canopy cover outputs were binned into 10 classes (with a bin width of 10%) and landscape diversity was calculated using the Shannon-Weiner Index [30]. Relative contagion (RC) [31] was also quantified, which quantifies spatial homogeneity

based on adjacency with a higher RC indicating less complex forests with greater spatial homogeneity. Lastly, to better understand the impacts that treatment within JCOS boundaries may have on forest structure and heterogeneity at the landscape scale, these metrics were calculated at the landscape scale for both untreated and treated scenarios.

Results

Meyer Ranch Park

Based on this simulation of treatments to restore historical ranges of forest structure, restoration treatments are expected to improve many aspects of forest heterogeneity at both Meyer Ranch Park and Reynolds Park (Figure 5 top panels; Table 1). At MRP, restoration simulations

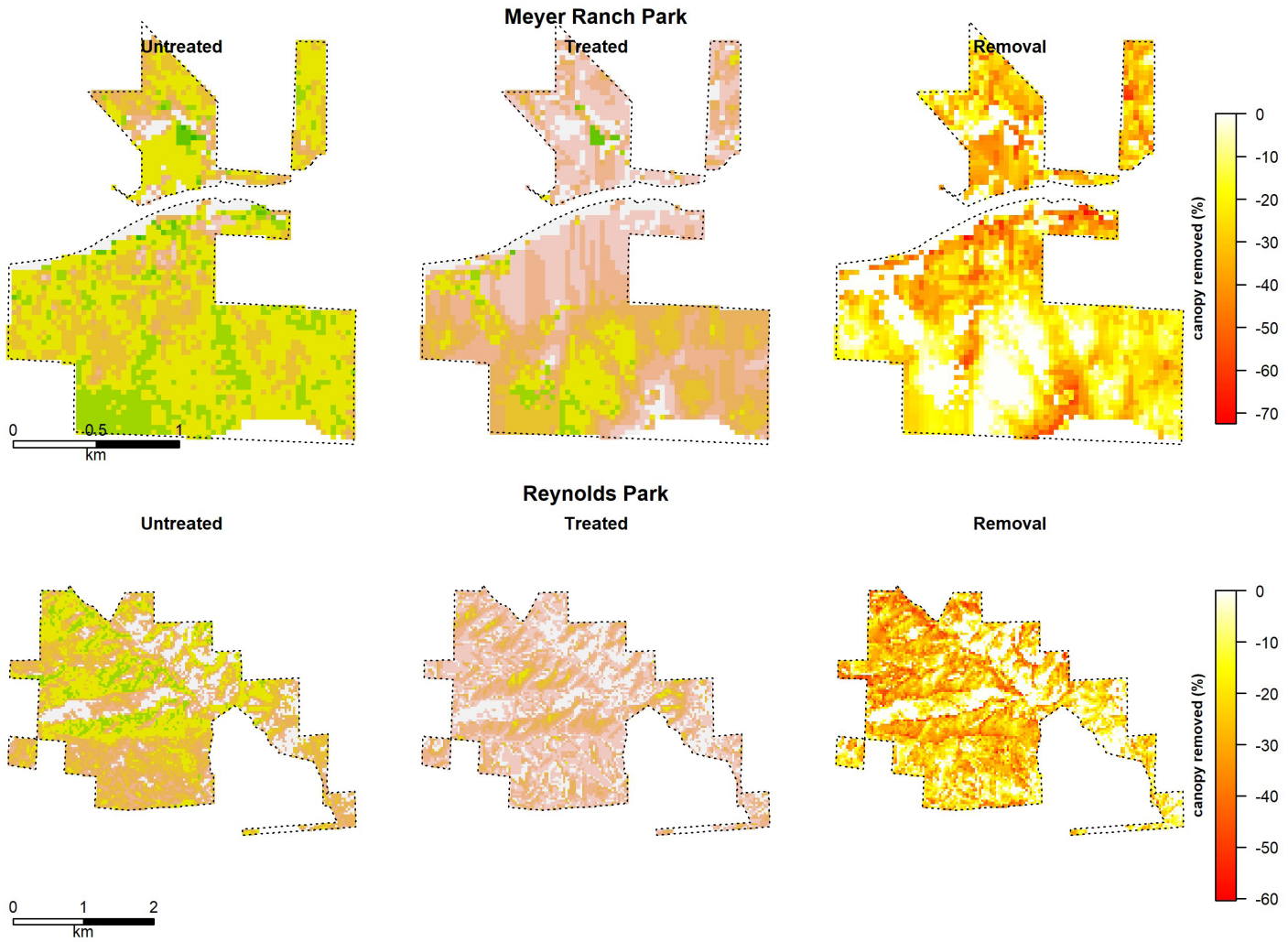


Figure 5. Change in canopy cover at Meyer Ranch Park and Reynolds Park showing canopy cover in each site before treatment (left panels), canopy cover following simulated restoration treatments (center panels), and difference between treated sites and untreated sites showing treatment intensity across each site (right panels). Legend for canopy cover same as Figure 4.

resulted in canopy cover decreasing from 50% to 29% while the increase in canopy cover c.v. from 0.28 to 0.53 indicates an increase in canopy cover variability. Restoration treatments are expected to roughly double the cover of openings from 0.5% to 1.1%. This increase is due primarily to increasing the number of gaps rather than gap size, as gap density is expected to increase from 0.01 ha⁻¹ to 0.02 ha⁻¹ while mean gap size is expected to remain at approximately 0.7 ha. Landscape diversity is expected to increase while relative contagion (spatial homogeneity) decreases after restoration treatments at MRP (Figure 5 top panels; Table 1).

Reynolds Park

Similarly, at RP, restoration simulations resulted in canopy cover decreasing from 39% to 19% while increasing canopy cover c.v. from 0.48 to 0.64 (Figure 5 lower panels; Table 1). Treatments at RP are expected to increase the cover of openings from 5.6% to 7.5%. As with MRP, this increase is due primarily to increasing the number of gaps rather than increasing existing gap size, as gap

density increased from 0.03 ha⁻¹ to 0.04 ha⁻¹, while mean gap size was relatively stable at 1.9 ha. Unlike MRP, at RP, landscape diversity is expected to decrease slightly while relative contagion increases slightly with restoration treatments (Figure 5 lower panels; Table 1).

Landscape-scale changes in forest heterogeneity

Overall, restoration treatments at MRP and RP improved several spatial heterogeneity metrics at the landscape scale (Figure 4; Table 1). Although canopy cover was reduced by approximately 20 percentage points in each individual treatment area, the effects at the landscape scale were more limited. Both MRP and RP treatments represent a small fraction of the overall landscapes considered (8% and 20% respectively), so their potential to make large changes in landscape metrics were limited. Nevertheless, simulated restoration treatments at MRP and RP decreased canopy cover 2-4 percentage points at the landscape scale while increasing canopy cover variability as measured by the coefficient of variation (Figure

Table 1. Changes in forest canopy structural, gap, and spatial complexity metrics before and after simulated restoration at Meyer Ranch Park and Reynolds Park assessed at the scale of treatments (sites) and landscapes.

Structural metric	Treatment scale			
	MRP		RP	
	Untreated	Treated	Untreated	Treated
Canopy cover mean (%)	50.3	29.4	38.6	18.6
Canopy cover c.v.	0.284	0.530	0.481	0.638
Gap cover (%)	0.52	1.08	5.59	7.52
Gap density (ha ⁻¹)	0.0076	0.0153	0.0291	0.0400
Mean gap size (ha)	0.68	0.70	1.92	1.88
Landscape diversity (H')	0.617	0.784	0.742	0.642
Relative contagion	0.430	0.277	0.234	0.294
Structural metric	Landscape scale			
	MRP		RP	
	Untreated	Treated	Untreated	Treated
Canopy cover mean (%)	45.1	43.5	40.6	36.7
Canopy cover c.v.	0.398	0.424	0.423	0.500
Gap cover (%)	5.19	5.23	4.30	4.68
Gap density (ha ⁻¹)	0.0093	0.0096	0.0221	0.0243
Mean gap size (ha)	5.55	5.43	1.95	1.93
Landscape diversity (H')	0.704	0.744	0.714	0.785
Relative contagion	0.342	0.314	0.371	0.324

4; Table 1). Landscape scale gap cover changed minimally at MRP, but increases in gap density increased gap cover 0.4 percentage points at RP. At both sites, landscape diversity increased and relative contagion decreased, indicating detectable increases in landscape complexity at the landscape scale as a result of treatments in JCOS lands.

Discussion

According to these simulations, restoration treatments at the MRP and RP have the potential to substantially increase forest structural heterogeneity—both at individual sites and at the landscape scale. Simulated treatments generally decreased canopy cover and increased canopy variability at the scale of individual treatments and at the landscape scale. Changes in gap cover at the individual treatments varied, with minimal increases at MRP and more dramatic increases at RP. Changes in gap structure occurred primarily through increases in gap number rather than expansion of existing gaps, as mean gap size was unchanged. Treatments at MRP and RP both increased landscape diversity and decreased relative contagion at the landscape scale, though they differed in their site-level effects. Taken together, these results indicate that restoration that explicitly aims to restore aspects of historic canopy structure and variability can enhance spatial heterogeneity within the treatments themselves, and have a notable impact on the surrounding landscape.

It should be noted that this simulation used relatively aggressive canopy removal with up to 60-70% removal in

some areas to reduce canopy cover within treatments to near historic levels (mean canopy cover of 18% and 35% in MRP and RP, respectively). Furthermore, the treatment simulations were intentionally designed to increase heterogeneity at multiple scales. Thus these simulations represent a best-case scenario for improving landscape-scale desired conditions within JCOS boundaries. In reality, although many restoration treatments aim to reduce canopy cover and increase spatial variability, often several factors such as social, logistical, and topographic limitations constrain restoration programs and outcomes may not reach historical densities and spatial patterns [8]. Use of mechanical treatments may be limited on steep slopes, and creation of larger treeless openings may be constrained on public lands. In addition, typical silvicultural treatments often focus on achieving uniform spacing and relatively similar density targets which can have a homogenizing effect on forest structure [8,32]. Such constraints were not considered in this simulation. If restoration treatments are more conservative, less extensive, or less spatially variable, forest heterogeneity may be relatively unchanged or even reduced within the treatment areas considered.

Although simulation analyses have some assumptions and limitations, these outputs can be useful for informing decisions about how restoration treatments may impact larger landscape processes. For example, treatments at Meyer Ranch Park have the potential to increase landscape diversity by 5.7% and reduce canopy homogeneity (relative contagion) by 8.4% (Figure 4; Table 2). Treatments at Reynolds Park are expected to increase landscape diversity

Table 2. Landscape scale changes in forest structural metrics at Myer Ranch Park and Reynolds Park. Effect sizes calculated as Effect size = (treated – untreated)/untreated.

Structural metric	-----Meyer Ranch Park -----			-----Reynolds Park -----		
	Untreat- ed	Treated	Effect size	Untreat- ed	Treated	Effect size
Canopy cover mean (%)	45.1	43.5	-3.5%	40.6	36.7	-10%
Canopy cover c.v.	0.398	0.424	6.4%	0.423	0.500	18%
Gap cover (%)	5.19	5.23	0.8%	4.30	4.68	9%
Gap density (ha ⁻¹)	0.009	0.010	3.1%	0.022	0.024	10%
Mean gap size (ha)	5.55	5.43	-2.3%	1.95	1.93	-1%
Landscape diversity (H')	0.704	0.744	5.7%	0.714	0.785	10%
Relative contagion	0.342	0.314	-8.4%	0.371	0.324	-13%
Park area (ha)	270			827		
Landscape area (ha)	3425			4123		
% of landscape		7.9%				20.1%
Area treated ≥ 20% canopy removal (ha)		140				436

by 10% and reduce canopy homogeneity by 13% (Figure 4; Table 2). Although treatments at Reynolds Park lead to larger changes in landscape complexity, this treatment was also much larger relative to the surrounding landscape; to realize these changes in landscape complexity requires 436 ha (1077 ac) treated with relatively high canopy removal ($\geq 20\%$) (Figure 4 lower right panel; Table 2). Conversely, although the treatment at Myer Ranch Park contributes smaller changes in landscape heterogeneity, those changes are realized with a much smaller footprint of 140 ha (346 ac) treated with high canopy removal ($\geq 20\%$) (Figure 4 upper right panel; Table 2).

Simulation analyses provide guidance on how proposed actions can contribute landscape-scale goals. Restoring elements of historic density and variability is one management goal in many ponderosa pine forests. However, managers often consider multiple objectives to spatial heterogeneity when planning restoration treatments, thus additional impacts such wildfire risk, enhancement of wildlife habitat, reduction of erosion risk, implementation feasibility, and other concern may be considered. Analytical frameworks have been proposed to address many of these concerns [19,20,22,33]. Moreover, combining simulation analyses into integrated frameworks to simultaneously consider treatment impacts on multiple resources can help quantify and clarify multiple objectives. This analysis modeled one potential restoration scenario where restoration treatment intensity was constrained to reach historical levels of canopy cover and variability. In practice, multiple types of treatments can be considered. For example, these analyses can be adjusted to simulate targeted fuel reduction treatments over smaller areas by adjusting model inputs to reflect outcomes of

such treatments based on available literature on expected impacts [7,8,22,34,35]. Simulation analyses such as the one reported above can be expanded to include a range of potential treatment types such as mechanical thinning, prescribed fire, or combinations of these actions as have been implemented in other studies [20]. In addition, various proposed treatment extents or intensities can also be considered to explore the potential impacts of a variety of actions [19,22]. Lastly, although the analytical framework is presented here as a way of assessing the potential outcomes of proposed treatments, it can also be combined with empirical data such as monitoring surveys or satellite imagery to document and evaluate outcomes of completed treatments. In this initial study, potential benefits of proposed restoration treatments on forest spatial heterogeneity were quantified for two proposed sites. Future work may expand to other concerns such as fire risk, wildlife value, and post-fire erosion hazard to address a number of resource concerns at landscape scales.

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