2018 Ecological Monitoring Report for Peaks to People Water Fund Demonstration Sites

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COLORADO FOREST RESTORATION INSTITUTE

COLORADO STATE UNIVERSITY

Peaks to People Water Fund

The Nature Conservancy

Colorado Forest Restoration Institute

The Colorado Forest Restoration Institute is a science-based outreach and engagement organization hosted by the Department of Forest and Rangeland Stewardship and the Warner College of Natural Resources at Colorado State University. We lead collaborations between researchers, managers, and stakeholders to generate and apply locally-relevant, actionable knowledge to inform forest management strategies. Our work informs forest conditions assessments, management goals and objectives, monitoring plans, and adaptive management processes. We help reduce uncertainties and conflicts between managers and stakeholders, streamline planning processes, and enhance the effectiveness of forest management strategies to restore and enhance the resilience of forest ecosystems to wildfires. We complement and supplement the capacities of forest land managers to draw upon and apply locally-relevant scientific information to enhance the credibility of forest management plans. We are trusted to be rigorous and objective in integrating currently-available scientific information into forest management decision-making.

Cover photo:
These photos were taken at eye level the same plot before (2016) and after (2018) treatment at the Ben Delatour Scout Ranch. These photos are taken as part of CFRIs monitoring protocols.

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Executive Summary

The Peaks to People Water Fund is working to improve watershed health and protect water resources on the northern Colorado Front Range by using active forest management in areas of high wildfire risk and potential impact to water resources. Peaks to People Water Fund completed a selection process to establish forest restoration projects demonstrating the benefits of forest management in moderating wildfire behavior and protecting water resources from negative impacts associated with postfire soil erosion and sedimentation. The goals of establishing demonstration sites were to enhance communication of connections between forest and watershed health, attract investors, promote water resource protection, and serve as a learning lab to enhance effectiveness of forest management. The two sites selected were Ramsay-Shockey in the Big Thompson watershed and the Ben Delatour Scout Ranch (Scout Ranch) in the Cache la Poudre watershed.

Peaks to People aims to manage forests such that wildfires are less severe, post-fire erosion is minimized, and valuable ecosystem services are preserved. Historically, lower elevation ponderosa pine forests burned primarily at low and moderate severity with scattered patches of high severity effects, which maintained open, low density forests that were resilient to fire disturbances. However, fire suppression and other land management practices over the past century have led to increased tree density that reduces forest resiliency under current and future climates. Forest restoration goals in lower elevation ponderosa pine forests aim to restore and maintain long-term low-density forests, openings, and complex, varied forest spatial patterns. Such structures can support characteristic low- to mixed-severity fire and create and maintain conditions that support resilience and resistance to disturbances such as wildfire and insect and disease outbreaks.

Figure 1: Before and after photos from Ramsay-Shockey

The Colorado Forest Restoration Institute at Colorado State University worked closely with the Colorado Chapter of The Nature Conservancy and other partners to lead monitoring at the demonstration sites to assess how projects aligned with Peaks to People program goals and objectives. Restoration effectiveness monitoring incorporates a comprehensive, multi-scale approach that enhances our understanding of current treatment effects on wildfire behavior and improves future forest management. In this report, we combine field-based measurements of forest and fuel structure, remote sensing techniques, and stand- and landscape-scale fire behavior modeling to measure cumulative ecological effects of forest restoration treatments on fire behavior and watershed health. Additional goals of the monitoring program include peer-to-peer learning and collaboration among forest and fire managers, which will improve future project outcomes.

During summer 2016, Ramsay-Shockey and Scout Ranch were targeted for forest restoration treatments consisting of mechanical tree harvesting. By spring 2017, nearly 100 acres of tree cutting was accomplished across both sites. In fall 2017, a 100 acre broadcast prescribed burn at Scout Ranch reintroduced fire to further reduce risk of high intensity wildfires and restore ecological processes. At both Scout Ranch and Ramsay-Shockey, fire behavior modeling informed by field surveys suggests that forest restoration activities contributed to desired forest structural conditions, though enhanced forest resilience to wildfire was most evident in stands at Scout Ranch that included prescribed broadcast burning. Prescribed fire at Scout Ranch in areas that weren't thinned reduced key metrics of effective fuel reduction projects. Average tree crown base height (CBH) was raised by 26 ft. and there was a 46% reduction in fine woody surface fuel loading. Mechanical thinning followed by prescribed fire raised average tree CBH by 5 ft. and reduced surface fuel loading by 2%; if precipitation had not occurred during the burn, effects of the prescribed fire likely would have been greater. Regardless, these changes promoted fuel conditions that can support a more characteristic low- to mixed-severity fire regime dominated by surface fire. When thinning treatments reduced tree density near historical reference conditions, the likelihood of high severity crown fire also decreased. However, at Ramsay-Shockey, mechanical thinning with modest overstory removal that did not remove residual slash had limited effects one year after treatment on reducing potential fire intensity and post-fire tree mortality.

Figure 2: An old-growth ponderosa pine at Ramsay-Shockey.

While tree density remained high in some areas of Ramsay-Shockey following thinning, decreased forest cover and increased frequency of large gaps in forest cover indicate the treatment made incremental progress towards fuels reduction and other forest health objectives. At Ramsay-Shockey, we found that forest restoration treatment decreased tree canopy cover (44% to 35%) and increased coverage of gaps from 25% to 40%. Gap size distributions show that Ramsay-Shockey restoration treatments generally shifted gap cover from many small gaps (≤ 2 acres) to fewer, larger gaps (> 2 acres). At Scout Ranch, gap coverage increased from 41% to

46% following thinning treatments as many small gaps combined to form larger gaps. Restoration treatments at both sites decreased overall tree density, and increased the size, size variability, and aggregation of gaps towards desired complex forest structure.

The Peaks to People Watershed Investment Tool models fire behavior in FlamMap using fuels data from the LANDFIRE program to estimate the impact of forest restoration treatments on fire behavior and effects. We compared fire behavior predictions from the Watershed Investment Tool to fire modeling using field survey data collected at each demonstration site. We found that the Watershed Investment Tool predicted more intensive fire behavior, including more passive and active crown fire. Most of this difference can be explained by differences in fire behavior fuel models and tree canopy base height. If LANDFIRE consistently under-predicts canopy base height, future analyses may need to adjust fuel structure inputs used by the Watershed Investment Tool to more accurately estimate benefits of forest fuel reduction for watershed protection.

Peaks to People stakeholders participated in field data collection as part of the monitoring process and provided valuable insights into the application of monitoring data. In turn, fire and forestry professionals learned ecological measurement techniques that will improve outcomes on other projects, expanding the impact of the demonstration sites. Participants from over 10 agencies collaborated and assisted Colorado Forest Restoration Institute in the data collection. Ramsay-Shockey and Ben Delatour Scout Ranch now serve as demonstration sites that show the effectiveness of cooperation and peer-to-peer learning. Both sites have hosted multiple visits from potential water fund investors, and serve to demonstrate connections of forest and watershed health to new audiences. They provide an open-air forum for managers, researchers, and stakeholders to engage in collaborative discussion about forest ecology and management.

Introduction

The Peaks to People Water Fund is working to improve watershed health and protect water resources on the northern Colorado Front Range by using active forest management in areas of high wildfire risk and potential impact to water resources. Forest restoration under Peaks to People is focused on managing forest structure and fuel loads to reduce the potential for active crown fire and high-severity fire effects over large watersheds. The program emphasizes other ecological and social values, such as habitat for wildlife, protection of homes and infrastructure, and recreation opportunities.

Central to the Peaks to People Water Fund is the establishment of on-the-ground projects demonstrating the benefits of forest management in moderating wildfire behavior and protecting water resources from negative impacts associated with post-fire soil erosion and sedimentation. By establishing open-air forums to discuss connections of forest and watershed health, Peaks to People hopes to enhance communication of connections between forest and watershed health, attract investors, and promote water resource protection. Throughout winter 2016, Peaks to People carried out a site selection process (Peaks to People Water Fund, 2016b) which resulted in the development and implementation of forest management actions at demonstration sites in two focal watersheds:

- Big Thompson Watershed: Ramsay-Shockey
- Cache la Poudre Watershed: Ben Delatour Scout Ranch

Mechanical forest management treatments at each demonstration site began in summer 2016 and were completed by spring 2017. The Colorado Forest Restoration Institute (CFRI) at Colorado State University (CSU), the Colorado Chapter of The Nature Conservancy (TNC) and other partners led an effectiveness monitoring program to assess how these projects achieved management goals and desired conditions. The monitoring program aims to provide information that supports adaptive management and facilitates peer-to-peer learning.

Management Goals and Desired Conditions

Forest management plans and prescriptions were developed to describe management goals, desired conditions, and guidelines for implementation (Peaks to People Water Fund, 2016a, 2016). Forest management goals for Ramsay-Shockey and Ben Delatour Scout Ranch (hereafter Scout Ranch) were to (1) create open, low-density ponderosa pine stands characteristic of historical conditions, (2) reduce risk of high-severity wildfire, and (3) increase resiliency to future disturbances. Desired forest conditions include openings and complex forest structural conditions that are expected to support characteristic-low to mixed-severity fire and resilience and resistance to insect and disease outbreaks forests.

While monitoring to date has focused on wildfire and forest health, broader project goals informed the site selection and influenced forest management prescriptions. These additional management objectives included: improved conditions for hydrologic function; wildlife habitat; aesthetics and recreational opportunities; supporting forest products industry; and value for Peaks to People demonstration and outreach activities.

Demonstration Project Descriptions

Ramsay-Shockey

The project is located in the Big Thompson Watershed on the Larimer County Ramsay-Shockey Open Space and adjacent State Land Board land near County Road 18E approximately 18 miles west of Loveland, Colorado (40.36°, -105.30°). Both properties contribute to Pinewood Reservoir, an important water resource managed by Northern Water as part of the Colorado-Big Thompson Project.

The project area covers approximately 70 acres across both the Open Space and State Land Board properties and is divided into three management units (Figure 3). Unit A (11 acres) is located on the Ramsay-Shockey Open Space. Unit B (22 acres) and Unit C (35 acres) are located on State Land Board property. In units A and B, slash (woody biomass such as branches, small trees, and other woody material generated from the mechanical treatments and not removed from

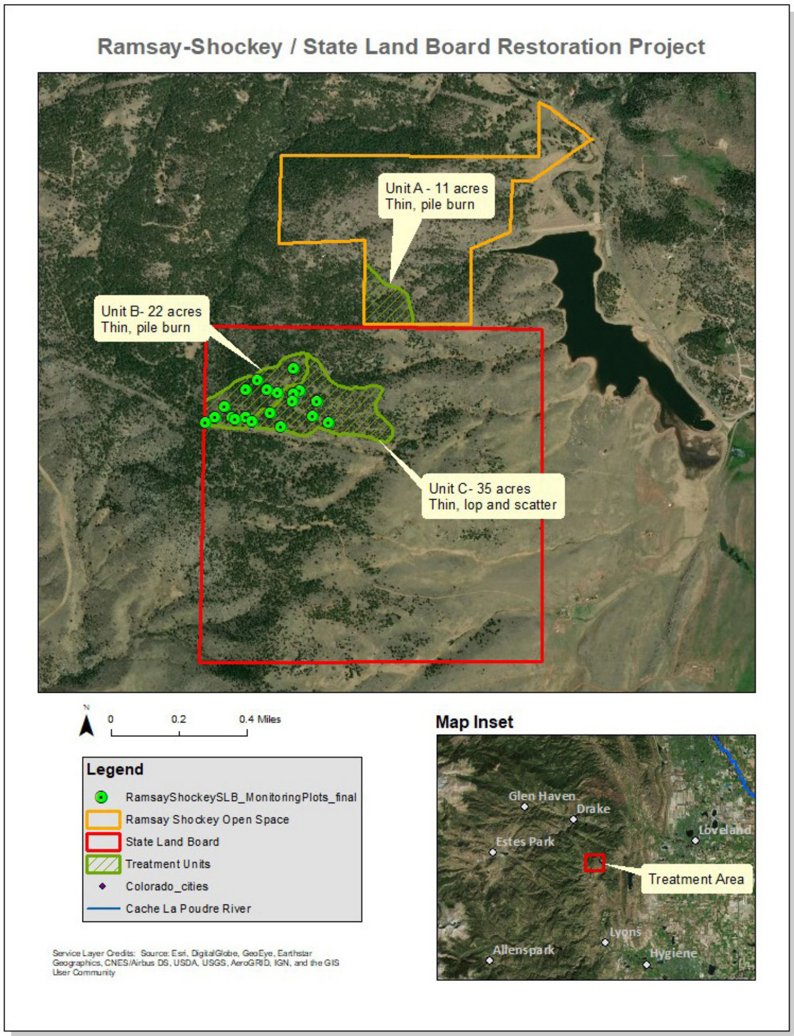

Figure 3: Location of Ramsay-Shockey site and monitoring plots

the site) was designated for piling and burning. In Unit C all slash was lopped and scattered throughout the unit. The treatment methods and objectives for overstory structure and composition were the same across units as described in the management goals above. Larimer County Emergency Services implemented the mechanical treatment in all units by felling trees with chainsaws and manually piling or lopping and scattering slash according to the management plan for each unit. More detailed treatment information is available in Peaks to People (2016c).

Scout Ranch

Scout Ranch is located within the Elkhorn Creek sub-watershed of the Cache la Poudre Watershed near Red Feather Lakes Rd and Rd 68C approximately 40 miles west of Fort Collins, Colorado (40.74°, -105.50°). Scout Ranch represents a significant private land holding (~3200 acres) within a landscape otherwise consisting mostly of public land managed by the U.S. Forest Service Arapaho and Roosevelt National Forest. The property sits on Elkhorn Creek, an important tributary to the main stem of the Cache la Poudre River.

The Scout Ranch project area covers approximately 185 acres on the southern end of the property and is adjacent to an existing 85 acre treatment area. Thinning occurred on approximately 29 acres in areas where forest density and hazardous fuels were highest (Figure 4). The subsequent prescribed broadcast burn was completed across a larger area of 98 acres that encompassed the mechanically harvested forest areas, as well as forests not mechanically harvested. Morgan Timber Products used feller bunchers and processers to complete mechanical mitigation activities. Loggers skidded all biomass to landings for processing and sorting, and piled slash at the landings for later burning. The forest structure and composition goals were similar to Ramsay-Shockey as described above.

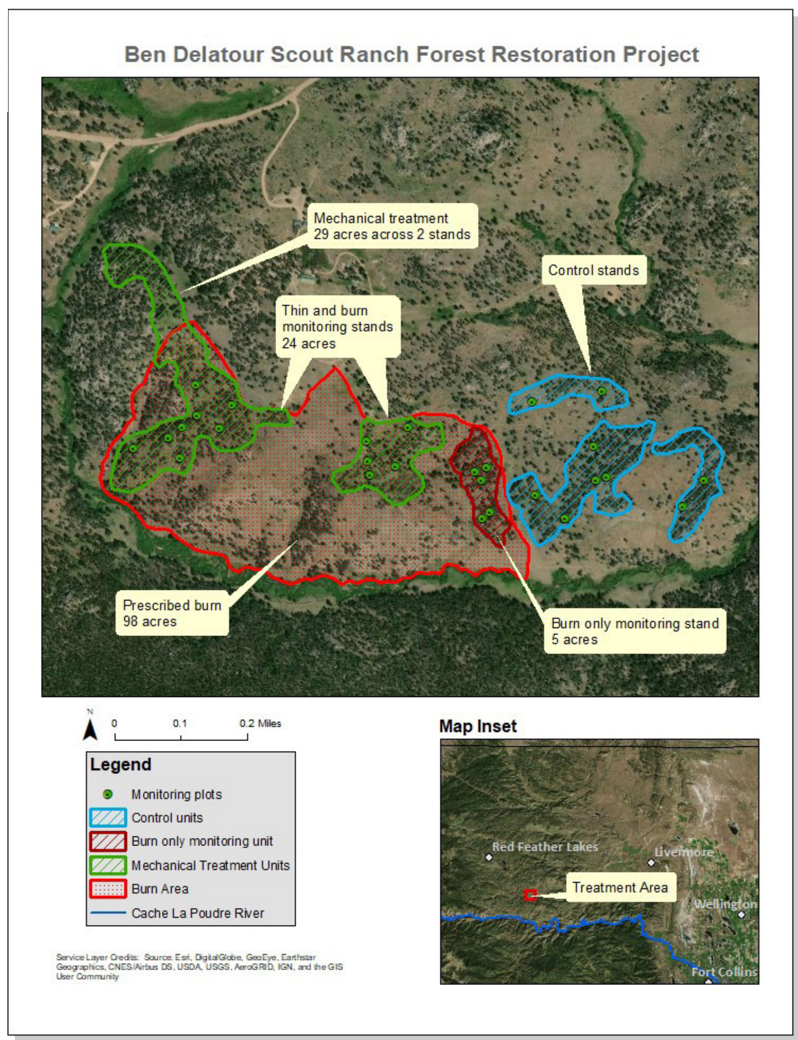

Figure 4: Location of the Scout Ranch site and monitoring plots

Monitoring and Evaluation

Projects funded by the Peaks to People Water Fund follow a process of planning, implementation, and project evaluation as outlined in the Peaks to People Operations Plan (Section 2 Participation in the Water Fund). Following the development of project goals and desired conditions, the project evaluation phase applies monitoring criteria to assess project performance and evaluate whether management goals and objectives were met. Peaks to People field monitoring guidelines are under development and will be revised using information from demonstration site monitoring. We evaluated wildfire and forest health objectives using a comprehensive, multi-scale approach, informed by two techniques:

1. Field surveys of forest structure and fuel loading to model fire behavior and effects before and after treatment using the Forest Vegetation Simulator (FVS).
2. Remote sensing techniques to quantify forest cover and gap distribution at a project scale.

Monitoring Methods

Field Sampling

To assess changes in fire behavior and forest dynamics at Scout Ranch and Ramsay-Shockey, we conducted field-based surveys to measure overstory density and composition, forest canopy cover, understory species composition, and fuel loading before and after mitigation activities. CFRI applied two complimentary sampling protocols at the Peaks to People demonstration sites, the Simple Plot and Mothership Plot methods. Simple Plot methods are intended to rapidly quantify fuel loading, forest structure and composition, describe the dominant shrub and herbaceous vegetation at the site, and require minimal botanical knowledge to complete. Mothership Plot methods are designed to capture comparable metrics of fuel loading and forest structure and composition while including more intensive measures of vegetation cover and species composition, and plant diversity. More details on specific measurement protocols are available on the CFRI website (CFRI, 2016a, 2016b, 2017, 2018b, 2018a).

We selected two treatment areas at each site for monitoring: Elkhorn Unit 2 at Scout Ranch, which contained a thin and burn area as well as a burn only area (Figure 4), and Ramsay-Shockey Units B and C (Figure 3). We also installed monitoring plots at Scout Ranch in an adjacent forested area that did not receive mechanical thinning or prescribed fire to serve as a control unit for future analyses of changes in plant species composition and abundance over time. Each demonstration site contained 14-20 plots. Each monitored treatment area within the demonstration sites contained 5-13 plots. We randomly established monitoring plots across Scout Ranch and Ramsay-Shockey Unit B. Ramsay-Shockey Unit C was an exception, as eastern portions of the unit had already been treated before monitoring began. We restricted parameters for monitoring plots in Ramsay-Shockey Unit C to untreated areas, and

Table 1: Description of demonstration project areas with CFRI monitoring plots.

Project Site Name	County	Elevation (ft)	Unit Name	Years sampled	Number of plots sampled	Implementation method(s)
Scout Ranch	Larimer	7590	Elkhorn 2 (thin & burn)	2016, 2017, 2018	13	Mechanical thin-whole tree harvest, followed by broadcast burn
			Elkhorn 2 (Burn only)	2017, 2018	5	Broadcast burn
Ramsay-Shockey	Larimer	7230	B	2016, 2017	11	Mechanical thin, slash pile burned
			C	2016, 2017	9	Mechanical thin, slash lopped and scattered

randomized plot locations within those parameters. We sampled plots from 2016-2018 (Table 1). At Scout Ranch, we used the more intensive CFRI Mothership Plot sampling protocol for the majority of plots, and supplemented our data with an additional 5 plots measured using the Simple Plot protocol. We permanently marked plot locations with stakes and recorded coordinates with Garmin eTrex GPS units. During each monitoring visit, we captured photographs of surface fuels, tree canopy, and at eye-level to provide visual documentation of changes in forest conditions.

Here, we define seedlings as trees less than 4.5 ft. tall. Saplings are trees greater than 4.5 ft. tall and less than 5 in. diameter at breast height (DBH, 4.5 ft.). We measured seedlings and saplings in a 1/100th acre fixed radius plot, and catalogued trees using a 10 basal area factor prism. Fine woody fuels include dead wood on the forest floor less than 3 in. diameter; these fuels are further divided into timelag classes based on the amount of time it takes fuel to equilibrate with ambient humidity. Fine woody fuels are classified as 1-hour (<0.25 in. diameter), 10-hour (0.25-1 in. diameter), and 100-hour (1-3 in. diameter) fuels. We estimated the loading of fine woody fuels using the photoload method (Keane & Dickinson, 2007) and corrected for bias by applying a calibration equation (Morici & Cannon, 2018; Tinkham et al., 2016)Any dead wood on the forest floor greater than 3 in. diameter is classified as course woody fuel. These are measured within a 1/10th acre circular plot.

Table 2: Categories used to quantify soil and vegetation burn severity (CFRI, 2018c; USDI National Park Service, 2003).

	Unburned	Scorched	Lightly Burned	Moderately Burned	Heavily Burned
Substrate	Not burned	Litter partially blackened; duff nearly unchanged; wood/leaf structures unchanged	Litter charred to partially consumed; duff layer not altered over the entire depth; surface appears black; woody debris is partially burned; logs are scorched or blackened but not charred	Litter mostly to entirely consumed, leaving coarse, light colored ash; duff deeply charred, but underlying mineral soil is not visibly altered; woody debris is mostly consumed; logs are deeply charred	Litter and duff completely consumed, leaving fine white ash; mineral soil visibly altered; sound logs are deeply charred, and rotten logs are completely consumed.
Vegetation	Not burned	Foliage scorched and attached to supporting twigs	Foliage and smaller twigs partially to completely consumed; branches mostly intact	Foliage, twigs, and small stems consumed; some branches still present	All plant parts consumed, leaving some or no major stems/trunks; any left are deeply charred

In addition to the protocols used to capture the effects of forest restoration treatments on forest and fuel structure and fire behavior, we developed protocols to describe immediate fire severity effects of the broadcast burn at Scout Ranch by assessing burn severity of vegetation and soil (CFRI, 2018c). The prescribed burn implemented by The Nature Conservancy and partners took place on September 22, 2017, and we measured fire effects on all plots from October 24th through November 6th, 2017. At each plot, we classified substrate and vegetation burn severity into five categories, from unburned to heavily burned, in ten to twelve 36 in.^{2} subplots (Table 2). We calculated percent of substrate burned from 200 observations on eight 25 ft. transects. We tagged individual overstory trees and saplings to track primary predictors of fire related mortality including percent of crown volume scorched, maximum height of canopy scorch, and the maximum height of char on the trunk.

Fire Behavior and Effects: FFE-FVS Modeling

To understand how changes in forest structure and surface fuels altered fire hazard, we conducted fire modeling based on field surveys of pre-treatment and post-treatment stands using the Fuels and Fire Extension to the Forest Vegetation Simulator (FFE-FVS; Reinhardt & Crookston, 2003). FFE-FVS is a widely used platform to measure potential fire behavior change following fire mitigation treatments (Battaglia et al. 2008; Johnson et al. 2011; Reinhardt et al. 2010). All modeling runs used the Central Rockies variant in FVS. Field-collected monitoring data for trees, saplings, seedlings, woody fuels, and surface fuels were processed by FFE-FVS, which selected up to two of 53 standard fire behavior fuel models for each stand (Anderson, 1982; Scott & Burgan, 2005).

We compared fire simulations for pre-treatment and post-treatment stands to evaluate how mitigation activities changed fire hazard using FFE-FVS. We analyzed mitigation effects on fire behavior and fire effects, including torching index, crowning index, fire type, surface flame length, total flame length, and tree mortality as described below. Torching index is the 20-foot windspeed needed to initiate crown fire activity, which is influenced by surface fuels, surface fuel moisture, canopy base height, slope steepness, and wind reduction by the canopy. Crowning index is the 20-foot windspeed needed to maintain active crown fire, and is influenced by canopy bulk density, slope steepness, and surface fuel moisture content. We modeled torching and crowning indexes under severe fire conditions. For both torching index and crowning index, higher windspeed values are desirable. FFE-FVS categories of fire type include surface, passive crown, conditional crown, and active crown fires. Surface fire primarily burns on the forest floor and is predicted to occur when the input windspeed is less than both the torching and crowning indexes. Passive crown fire burns the crowns of individual and groups of trees and is predicted when the input windspeed is greater than the torching index and less than the crowning index. Conditional crown fire is predicted when active crown fire is expected, but torching is not. FFE-FVS considers conditional crown fire to be active crown fire in modeling fire behavior and effects. Active crown fire spreads between tree crowns and is predicted when the input windspeed is greater than both the torching and crowning indexes.

Despite its widespread use, there are several limitations to consider when interpreting modeled fire behavior and effects from FFE-FVS. Cruz & Alexander (2010) found the underlying models and linkages used in FFE-FVS result in a significant underprediction bias for crown fire, thus crown fire may be more common than indicated in our modeling results. Fire modeling runs in FVS take place under constant conditions and do not include changes in fire activity due to variation in weather, topography, or fuels. Additionally, the data collected during monitoring is used to assign one or more pre-determined fire behavior fuel models, which are limited in number and do not allow for a continuous spectrum of fire behavior governed directly by the input data. Thus, modest differences in stand conditions may not lead to detectable differences in modeled fire behavior. While FVS accepts detailed tree inventory data, it does not allow for customization of the live herbaceous and shrub layers. FVS predicts herbaceous and shrub loading based on dominant tree species and modeled

Table 3: Weather and fuel moisture values used for fire behavior modelling with FFE-FVS based on fuel moisture and temperature information from RAWS data.

Fire Conditions	Wind (MPH)	Temp (° F)	Fuel Moisture Conditions (%)						
			1-hr	10-hr	100-hr	1000-hr	Duff	Live Woody	Live Herb
SEVERE	20	90	4	4	5	10	15	70	30
MODERATE	6	77	8	10	12	16	125	120	120

canopy cover. Finally, modeled fire behavior in FVS does not account for the impacts of fire suppression actions. Some treatments may facilitate suppression actions, for instance a reduction in fire intensity may allow for direct suppression tactics, and reducing tree canopy cover may increase fire retardant penetration.

Comparison to Watershed Investment Tool

The Peaks to People Watershed Investment Tool models fire behavior with the FlamMap 5.0 spatial fire modeling system (Finney et al. 2015) under 97th percentile fuel and weather conditions using gridded fuels data from the LANDFIRE program (LANDFIRE 2014). The Watershed Investment Tool simulates stylized fuel treatment effects based on typical restoration outcomes to estimate the benefit of mechanical only, prescribed fire, and combined forest restoration treatments (Jones et al, 2016; Gannon et al., in press). Field-based assessment of treatment effects may differ because baseline fuel conditions do not match estimates from LANDFIRE or the actual treatment effects differ from the typical fuel treatments. The Watershed Investment Tool models crown fire activity as a proxy for soil burn severity based on the co-registered 30-meter resolution fuel and topography data, fuel moisture, and wind speed. In contrast, FFE-FVS applies the same basic models of fire behavior to fuel conditions modeled from the field inventory data and assumes level terrain. We compared crown fire activity predictions from the Watershed Investment Tool with field-based data modeling with FFE-FVS. We explain differences in predicted crown fire activity due to differences in data sources and model assumptions.

Forest Canopy Cover and Gap Size Distribution

Management goals included creating large gaps and increasing forest complexity to enhance forest health. To quantify progress towards these goals, we measured changes in canopy cover and gap structure using supervised classification of pre- and post-treatment imagery of each site into tree canopy and openings using protocols based on Cannon et al. (2018). We acquired pre- and post-treatment imagery for Ramsay-Shockey from WorldView-02 satellite on September 2015 and April 2017, respectively (Figure 5-A). At Scout Ranch, pre- and post-mechanical treatment imagery was available from Quickbird-02 (25 May 2013) and Worldview-02 (12 April 2017). Imagery following the prescribed burn is not currently available for Scout Ranch through public sources and thus could not be included in the analysis. We georeferenced all imagery and resampled satellite imagery to a 3-meter resolution for consistency across monitoring projects. We derived the normalized difference vegetation index to aid in classification (Lillesand et al., 2014). To classify imagery, we stratified approximately

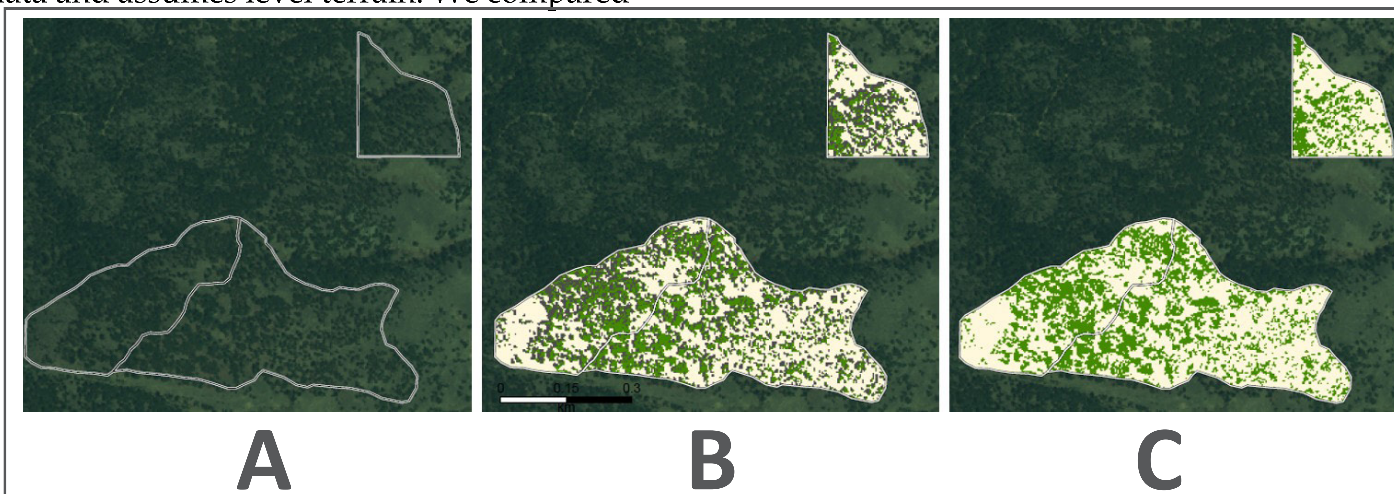

Figure 5: Example imagery from Ramsay-Shockey treatment units illustrating satellite imagery classification process. (A) Example satellite imagery and treatment unit boundaries. (B) Classified imagery indicating canopy (green) openings (yellow), and shadows (grey). (C) Reclassified imagery showing canopy and openings only.

100 training areas in each image and used supervised random forests to classify each image into canopy, openings, and shadows (Figure 5-B). To test the accuracy of the classification, we calculated a confusion matrix by withholding a random subset of 20% of the training areas (Congalton & Green, 2008). Regions classified as shadows were then re-classified into canopy and openings using a grey-level threshold of the Normalized Difference Vegetation Index (NDVI) (Figure 5-C).

We delineated "large gaps" as all continuous regions with <5% canopy cover over a 0.1 acre area (40 foot radius). Although gaps can be defined variously depending on the ecological process of interest, we chose this scale because resource abundance and regeneration growth are governed by tree density in the surrounding 40 ft. radius (Boyden et al., 2012). From the resulting classified rasters and delineated gaps, we calculated pre- and post-treatment cover of large gaps, and average canopy cover at a 30-meter scale. Using individually identified gaps, we calculated gap size distributions and assessed gap size variability using the coefficient of variation (standard deviation/mean) of gap size. Finally, we calculated gap decay coefficient (adapted from stand-replacing decay coefficient Collins et al., 2017), which is related to the proportion of area concentrated within gap interiors. Since forest structure management goals were the similar across units, we combined forest cover and gap distribution analyses across all treatment areas for each site. Performing forest cover and gap distribution analyses across larger areas rather than separately for individual treatment units allows landscape level assessment of forest heterogeneity.

Results and Discussion

Forest and Fuels Inventory

Overall, management goals for basal area and tree density were met following forest restoration activities in all monitored areas except Ramsay-Shockey Unit C (Table 4, Figure 6). At Ramsay-Shockey Unit B and Scout Ranch, thinning reduced live tree basal area by approximately 50% and tree density by approximately 60% as treatment prescriptions emphasized removal of smaller trees. Prescribed broadcast fire applied to an unthinned (burn only) stand at Scout Ranch resulted in a similar reduction to live tree density and basal area as the mechanical thinning. However, following the restoration treatment Ramsay-Shockey Unit C retained high tree density and remained well above the basal area target of approximately 40 ft.^{2}/acre, with residual basal area of 90 ft.^{2}/acre. Following restoration treatments, basal area at Ramsay-Shockey Unit B and both units at Scout Ranch are similar to historical reference conditions. However, Ramsay-Shockey Unit C was less congruent with management goals; basal area and forest density remain at the high end of reference conditions at similar sites for the northern Colorado Front Range. (Table 4). This could be the result of removing only small trees, or not removing enough trees within the stand to achieve the desired conditions. Additionally, some tree harvesting had already begun in the eastern portion of Unit C when monitoring started, so monitoring plots were established only in the western two thirds of the unit. Remote sensing canopy cover analysis across the entire Ramsay-Shockey unit indicates several large gaps and lower tree cover in the eastern portion of Unit C which were not included in ground surveys, so we suspect that the actual basal area and tree density across the entire unit is slightly lower than measured with our field plots. An important principle of restoring Front Range montane forests is to reduce tree density while maintaining a range of forest densities across the landscape (Addington et al., 2018); it appears all monitored treatment areas achieved this goal as indicated by the high standard deviation in residual basal area and tree density in each stand (Table 4).

Fine woody surface fuel loading was generally low in all monitored stands and remained low or decreased after treatment. Ramsay-Shockey Unit C was an exception, as lopping and scattering slash caused a notable increase in fine woody fuel load (Table 4). Coarse woody fuel loading also increased in Ramsay-Shockey Unit C. In the event of a wildfire, heavy coarse woody fuel loading could lead to increased soil heating as well as difficulty with fire containment and

	Before Treatment	After Treatment
Plot 17 in Ramsay-Shockey Unit C. While tree density was reduced, some areas remained more dense than desired.		
Plot 11 in Ramsay-Shockey Unit B. Tree density was substantially reduced throughout Unit B.		
Plot 2 in Scout Ranch Thin & Burn. Tree density was relatively low before treatment, and further reduced to meet desired conditions.		
Plot 11 in Scout Ranch Burn only. Live tree density was reduced by the prescribed fire to a similar degree as the Thin, though dead trees remain in the stand.		

Figure 6: Paired photographs taken before and after treatment within each monitored stand in Ramsay-Shockey and the Scout Ranch.

control (Brown et al., 2003). Pile burning at Ramsay-Shockey Unit B had not yet occurred by the post-treatment measurement visit, so coarse fuel load appeared to increase substantially, though pile burning is likely to greatly decrease loading of coarse woody fuels. Following the prescribed broadcast burn, coarse woody fuel loading decreased at both Scout Ranch stands. Prescribed broadcast fire, applied alone or following other treatments, is a promising method to immediately reduce woody surface fuels. However, the prescribed fire in the burn only stand at Scout Ranch resulted in nearly 50% mortality of tree basal area. While standing dead trees are beneficial for

Table 4: Mean tree basal area, tree density, fine and coarse woody fuel loading (± one standard deviation) across the two demonstration sites. Management Goal is from the management plan desired condition at each site (Peaks to People Water Fund, 2016a, 2016). Historical Reference data were cited in the management plans as a means to inform management prescription development. Ramsay-Shockey historical reference used (P. M. Brown et al., 2015); the Lady Moon site (Battaglia et al., 2018) was used as a proxy for the Scout Ranch.

Site	Unit	Phase	Live Tree Basal Area (ft^2/acre)	Live Tree Density (trees/acre)	Fine Woody Fuel Loading (tons/acre)	Coarse Woody Fuel Loading (tons/acre)
Ramsay-Shockey	B	Pre	79 ± 53	174 ± 149	1.2 ± 1.0	1.3 ± 1.3
		Post	46 ± 32	75 ± 72	0.8 ± 0.7	7.2* ± 6.3
	C	Pre	116 ± 35	257 ± 165	0.7 ± 0.5	1.3 ± 1.8
		Post	90 ± 38	143 ± 70	1.4 ± 1.4	5.9 ± 4.4
	Management Goal		*40 (Range 0-80)*	*N/A*	*N/A*	*N/A*
	Historical Reference		*25 (Range 0-74.5)*	*39 (Range 0-791)*	*N/A*	*N/A*
Scout Ranch	2 (Thin & burn)	Pre	69 ± 34	97 ± 63	1.2 ± 0.8	1.1 ± 1.3
		Post-Thin	31 ± 25	39 ± 47	1.2 ± 0.7	1.1 ± 0.9
		Post-Thin & burn	30 ± 25	39 ± 47	1.2 ± 1.1	0.9 ± 0.9
	2 (Burn)	Pre	68 ± 37	103 ± 73	0.7 ± 0.3	2.2 ± 2.1
		Post	36 ± 30	65 ± 70	0.4 ± 0.3	0.4 ± 0.5
	Management Goal		*30 (Range 0-60)*	*N/A*	*N/A*	*N/A*
	Historical Reference		*33 (Range 6-93)*	*53 (Range 24-69)*	*N/A*	*N/A*

* piles not yet burned by date of post-treatment measurement visit

some wildlife species, they will eventually contribute to the woody surface fuel pool in coming years and decades as branches and eventually tree boles fall to the ground.

Prescribed Fire Severity Assessment

At Scout Ranch, we assessed fire severity immediately following the broadcast burn in areas that were recently thinned as well as in a previously unthinned (burn only) area. All field-collected metrics of fire severity indicate that the thinned areas supported lower severity fire behavior compared to the burn only area (Table 5). Weather conditions during the burn also likely contributed to lower fire severity in thin & burn stands compared to the burn only stand. Thinned stands at Scout Ranch were largely unimpacted by the prescribed fire, with 70% of soil and vegetation observations unburned, compared to burn only areas where just 14% of soil and vegetation observations were unburned and 71% were heavily burned. Damage incurred to trees during the prescribed fires followed similar trends, with increased crown volume scorched in burn only stands. While fire-related tree mortality is best assessed 3-5 years following a burn, our preliminary results one year post-burn reveal that no trees in the thinned stands have yet been killed by the prescribed fire. In contrast, the burn in the burn only stand at Scout Ranch reduced live tree density from 103 to 68 trees/acre and basal area

Table 5: Observed mean ± one standard deviation of prescribed fire severity measurements at the Scout Ranch

	Thin & burn	Burn only
Percent Surface Burned	23.0 ± 27.0	39.3 ± 18.1
Overstory Crown Volume Scorch (%)	18.9 ± 37.1	94.4 ± 10.4
Overstory Stem Char Height (ft)	4.6 ± 9.6	51.0 ± 22.4

from 65 to 36 ft.^{2}/acre, which was comparable to the reduction by thinning alone. Additional tree mortality may occur over the next several years in the burn only stand due to high crown volume scorch.

FFE-FVS Fire Modelling

Broadly, we found that thinning alone did little to change modeled fire hazard, but hazard was substantially reduced following the application of prescribed broadcast fire. Thinning treatments at Ramsay-Shockey were not predicted to dramatically reduce fire hazard, though in Unit B more intense thinning combined with piling residual slash for burning resulted in a slight improvement in predicted stand resistance to crown fire behavior. Unit C started with higher tree basal area and density than Unit B, but a similar number of trees were removed, and residual slash was lopped and scattered. As a result of this less intensive treatment, the change in predicted fire behavior at Unit C was negligible, with slightly decreased potential for active crown fire, but greatly increased potential for tree torching. Treatments that removed trees effectively reduced canopy bulk density; this is the primary variable that is reduced by treatments and has an influence on the crowning index in the FFE-FVS model. Crowning index in FFE-FVS is also influenced by slope steepness and surface fuel moisture, but restoration treatments cannot influence these variables. Torching is influenced by a number of variables affected by treatment, such as surface fuel loading, tree canopy base height, and wind reduction by the canopy. Following treatment in Unit C, surface fuels increased and average tree crown base height was unchanged. Thinning trees likely increased below-canopy windspeeds, overall increasing the potential for torching. Scout Ranch stands began with relatively low tree basal area (about 70 ft.^{2}/acre) and density (about 100 trees/acre), and even before treatment both stands were predicted to support surface fire under severe fire weather and fuel moisture conditions. Forest restoration, through burning alone or in combination with thinning, further reduced tree density and increased the windspeeds predicted to initiate and sustain crown fire activity. Prescribed broadcast fire reduced surface fuel loading and raised average tree crown base height, which are key factors for increasing tree survival and improving forest resilience to wildfire.

Our fire behavior modeling results suggest that forest restoration activities moved both Ramsay-Shockey and Scout Ranch stands closer to desired conditions. Stand resilience to wildfire was enhanced by reducing tree basal area and density to historical levels and maintaining low fine woody surface fuel loading. Individual summaries of monitored stands are in Appendix A.

Comparison to Watershed Investment Tool

Fire behavior modeling with FFE-FVS indicated that most stands were predicted to burn as surface fire both before and after treatment (Table 6). The one exception is Ramsay-Shockey Unit C, where conditional crown fire was predict-ed before treatments and passive crown fire was predicted after treatments. In contrast, the Flam-Map-based predictions used in the Watershed Investment Tool include a greater proportion of passive and active crown fire in the stands before treatment, and most treatments are expected to moderate active crown fire to passive crown fire (Table 6). Prescribed fire is the only treatment method expected to reduce passive crown fire behavior to surface fire behavior. This effect was small at Scout Ranch only because most of the prescribed fire unit was already predicted to burn as surface fire in the pre-treatment condi-tion.

FFE-FVS predicted less passive and active crown fire than the Watershed Investment Tool, which can be explained by differences in data used to characterize canopy and surface fuels (Table 7; Table 8), the scale of modeling, and other modeling assumptions. Canopy cover estimates between LANDFIRE and field measurements are surprisingly close except for the burn only stand at Scout Ranch. The discrepancy between canopy cover estimates is a result of the fact that the field-based monitoring included only the portion of the prescribed fire unit with trees and the Watershed Investment Tool measures include the entire unit. Canopy bulk densi-

Table 6: Crown fire activity predicted using the FlamMap-based procedures in the Watershed Investment Tool and using field data with FFE-FVS. The Watershed Investment Tool results are presented as pre- and post-treatment percentages (by area) within each treatment unit. The field data was pooled into a single stand by treatment unit for modeling in FFE-FVS so only a single fire type prediction is made for each unit.

		Watershed Investment Tool (%)						**Field Data and FFE-FVS**	
		Pre-treatment			**Post-treatment**				
Project	**Unit**	**Surface**	**Passive**	**Active**	**Surface**	**Passive**	**Active**	**Pre-treatment Prediction**	**Post-treatment Prediction**
Scout Ranch	Thin only	4	26	70	4	83	13	Surface	Surface
	Burn only	53	30	17	55	33	12	Surface	Surface
	Thin & Burn	7	47	46	7	86	6	Surface	Surface
Ramsay-Shockey	A	10	8	81	10	88	2	NA	NA
	B	0	13	88	0	96	4	Surface	Surface
	C	2	22	76	2	92	6	Cond. Crown	Passive

Table 7: Stand averages of selected canopy fuel variables from LANDFIRE used in the Watershed Investment Tool and from field survey data. Canopy bulk density was modeled with FFE-FVS from the field data.

		Watershed Investment Tool		**Field Data and FFE-FVS**	
Project	**Unit**	**Pre-trt.**	**Post-trt.**	**Pre-trt.**	**Post-trt.**
Canopy Cover (%)					
Scout Ranch	Thin only	38.5	28.8	38.0	26.0
	Burn only	15.2	14.2	37.0	22.0
	Thin & Burn	29.2	22.4	38.0	26.0
Ramsay-Shockey	A	37.9	26.5	NA	NA
	B	42.4	30.1	37.0	30.0
	C	37.9	27.6	52.0	42.0
Canopy Base Height (m)					
Scout Ranch	Thin only	0.9	1.0	3.7	2.7
	Burn only	0.5	0.6	2.1	10.1
	Thin & Burn	1.1	1.3	3.7	4.3
Ramsay-Shockey	A	0.5	0.6	NA	NA
	B	0.5	0.6	3.0	3.4
	C	0.7	0.8	4.0	4.0
Canopy Bulk Density (kg/m^3)					
Scout Ranch	Thin only	0.074	0.049	0.078	0.037
	Burn only	0.035	0.031	0.059	0.012
	Thin & Burn	0.063	0.034	0.078	0.019
Ramsay-Shockey	A	0.090	0.054	NA	NA
	B	0.086	0.053	0.111	0.062
	C	0.086	0.055	0.160	0.098

Table 8: Surface fuels are represented by stylized fire behavior fuel models (FBFM) in both FlamMap and FFE-FVS (Scott & Burgan, 2005). FFE-FVS represents fuels as a mixture of fire behavior fuel models with percent weights used to combine predictions. LANDFIRE often includes more than two fuel models within the treatment unit extents so we approximated similar information by presenting the top two fuel models by area with their actual percent cover within the treatment unit. Note that FlamMap models fire behavior separately for each pixel and does not mix fuel models. This is just a convenient way of presenting similar information for each model.

		Pre-treatment				Post-treatment			
		FBFM 1		FBFM 2		FBFM 1		FBFM 2	
Project	**Unit**	**Code**	**%**	**Code**	**%**	**Code**	**%**	**Code**	**%**
Watershed Investment Tool									
Scout Ranch	Thin only	165	60.9	122	21.7	163	52.2	122	21.7
	Burn only	122	33.2	121	21.4	122	33.2	121	21.4
	Thin & Burn	165	61.5	122	28.4	165	55	122	28.5
Ramsay-Shockey	A	165	47.9	122	35.4	163	48.9	122	36.2
	B	122	42.7	165	37.5	122	42.7	163	33.3
	C	165	81.9	122	11.6	163	76.1	122	11.6
Field Data and FFE-FVS									
Scout Ranch	Thin only	186	85	202	15	186	93	185	7
	Burn only	186	94	202	6	102	56	101	44
	Thin & Burn	186	85	202	15	186	70	185	30
Ramsay-Shockey	A	NA	NA	NA	NA	NA	NA	NA	NA
	B	186	84	202	16	186	89	202	11
	C	186	81	202	19	202	64	203	36

ty is modeled by FFE-FVS from the stand inventory data because direct measurement requires destructive sampling of trees. Canopy bulk density measurements are generally within a factor of ± 2, which is acceptable given the difficulty of achieving a precise measurement. The largest and most consequential difference between the Watershed Investment Tool and field monitoring data is in canopy base height. Pre-treatment canopy base heights were ~4.5x higher as measured in the field than as predicted in LANDFIRE baseline data. Likewise, post-treatment canopy base heights were ~7x higher in the field than in LANDFIRE. Higher canopy base height reduces crown fire initiation, leading to less passive and active crown fire. Additionally, LANDFIRE and FFE-FVS selected different fire behavior fuel models (Table 8). FFE-FVS selects fuel models based on tree and surface fuel inventory data; it does not consider field measurements of understory plant composition or cover. LANDFIRE assigns more area to grass-shrub (121 and 122) and timber-understory fuel models (163 and 165), which produce more intense fire behavior and longer flame lengths than the timber litter fuel models (185 and 186) that dominate the FFE-FVS predictions. The consequence is that the LANDFIRE-based fire behavior modeling will predict more intense surface fire behavior that will more readily initiate crown fire.

The scale of measurement may also influence predictions. Field sampling plots were pooled into stands for fire modeling in FFE-FVS. Pooling plots reduces variability in crown fire activity within the stand; this variability is captured by the spatially explicit FlamMap modeling used in the Watershed Investment Tool. The FFE-FVS modeling assumed level terrain due to the varying slope and aspect of the individual plots. In the Watershed Investment Tool, FlamMap is run under a worst-case scenario of wind blowing uphill. All other factors being equal, increasing slope steepness intensifies fire behavior, so the FFE-FVS analysis likely underpredicts crown fire initiation in stands that have sloped terrain.

The burn only treatment increased canopy base height far more than the Watershed Investment Tool predicted (Table 7). The predicted change in canopy base height from prescribed fire came from Sierran Mixed Conifer Forests (Stephens & Moghaddas, 2005), which have much taller trees, and therefore higher canopy base heights. Forests on the Colorado Front Range are shorter in stature, so prescribed fires may raise canopy base height more. If this is a consistent trend, future analyses using the Watershed Investment Tool could be adjusted with local data, which will make prescribed fire more effective at reducing crown fire initiation. This highlights the importance of local data and continued monitoring, especially on prescribed fires in Colorado.

Remotely Sensed Canopy Cover and Gap Size Delineation

Overall, both Ramsay-Shockey and Scout Ranch forest restoration treatments contributed to desired conditions of decreased canopy cover and increased coverage and size of large gaps (Figure 7, Figure 8). Verification of classified imagery at Ramsay-Shockey indicated that overall accuracies for classified images were 96.5% for pre-treatment imagery and 98.4% post-treatment imagery. At Ramsay-Shockey, restoration treatments reduced canopy cover from 41% to 35%. Treatments also increased gap cover from 25% to 40% (Figure 7, upper panels). Several metrics indicate that forest restoration treatments increased the size, size variability, and aggregation of gaps (Figure 8, upper panels). The restoration treatment shifted gap cover so there is now a greater abundance of larger gaps (> 2.2 acres) instead of many small gaps (≤ 2.2 acres). Gap decay coefficient—a metric of gap disaggregation—decreased from 0.051 to 0.043. This change indicates that restoration treatments shifted gap areas from being predominately scattered across many small gaps, to being consolidated into fewer, larger gaps. The overall size variability—measured as the coefficient of variation of gap size—increased from 1.16 to 1.38, indicating that restoration treatments resulted in a larger variety of both large and small gaps.

Classified imagery at Scout Ranch had overall accuracies of 97.2% for pre-treatment imagery and 95.4% for post-treatment imagery. At this site, treatment reduced canopy cover from 44% to 41%, while gap cover increased from 41% to 46% in the stand that was treated mechanically (Figure 7, lower panels). Imagery was not available for the site after the prescribed fire, so we report only the changes from initial thinning treatments. Restoration treatments increased the average size and aggregation of gaps (Figure 8, lower panels). Prior to mechanical treatments, many small gaps and a few large gaps (> 40 acres) were already present. Restoration treatments combined many smaller gaps into larger, more aggregated gaps. Gap decay coefficient decreased slightly from 0.025 to 0.024, indicating greater gap consolidation after forest restoration treatments. The overall size variability of gaps, measured as the coefficient of variation of gap size, decreased from 4.08 to 3.55, indicating that disparity in gap size decreased following the mechanical treatment as multiple small gaps were consolidated into fewer larger gaps.

Collaboration and Knowledge Sharing

An essential component of ecological monitoring is addressing topics that are relevant to stakeholders. This goal is supported with two-way knowledge transfer between scientists and practitioners. To facilitate peer-to-peer learning, Peaks to People stakeholders were invited to participate in field data collection throughout the monitoring process. Forestry and fire managers informed monitoring strategies by sharing with scientists what information would be useful for management decisions. The impacts of this project expands beyond the demonstration sites, as fire and forestry professionals were trained in measurement techniques to help them gauge outcomes on other management projects and improve forest management elsewhere.

During a two-day monitoring workshop at

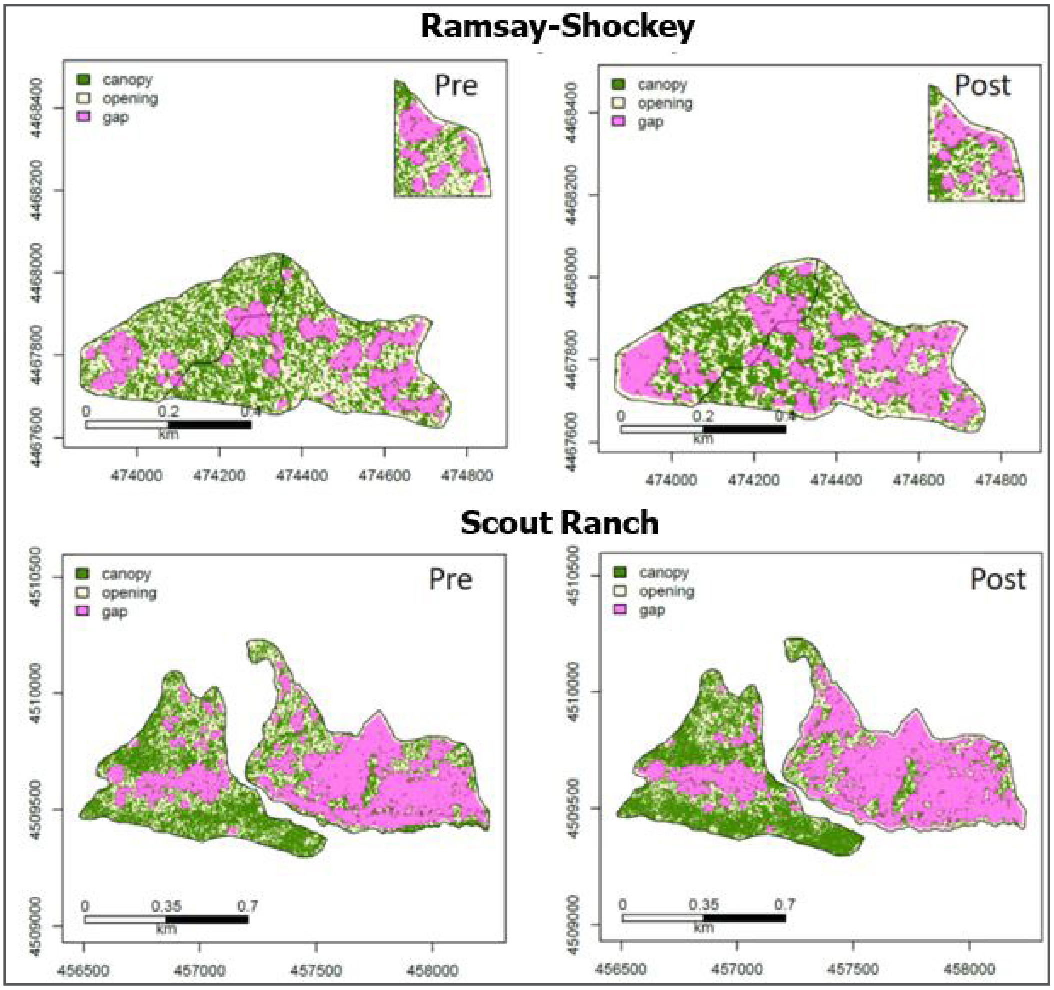

Figure 7: Canopy cover maps of Ramsay-Shockey (upper panels) and Scout Ranch (lower panels) cover of Ramsay-Shockey using analysis of aerial imagery. Canopy (green) and openings (yellow) are shown overlaid with large gaps (magenta).

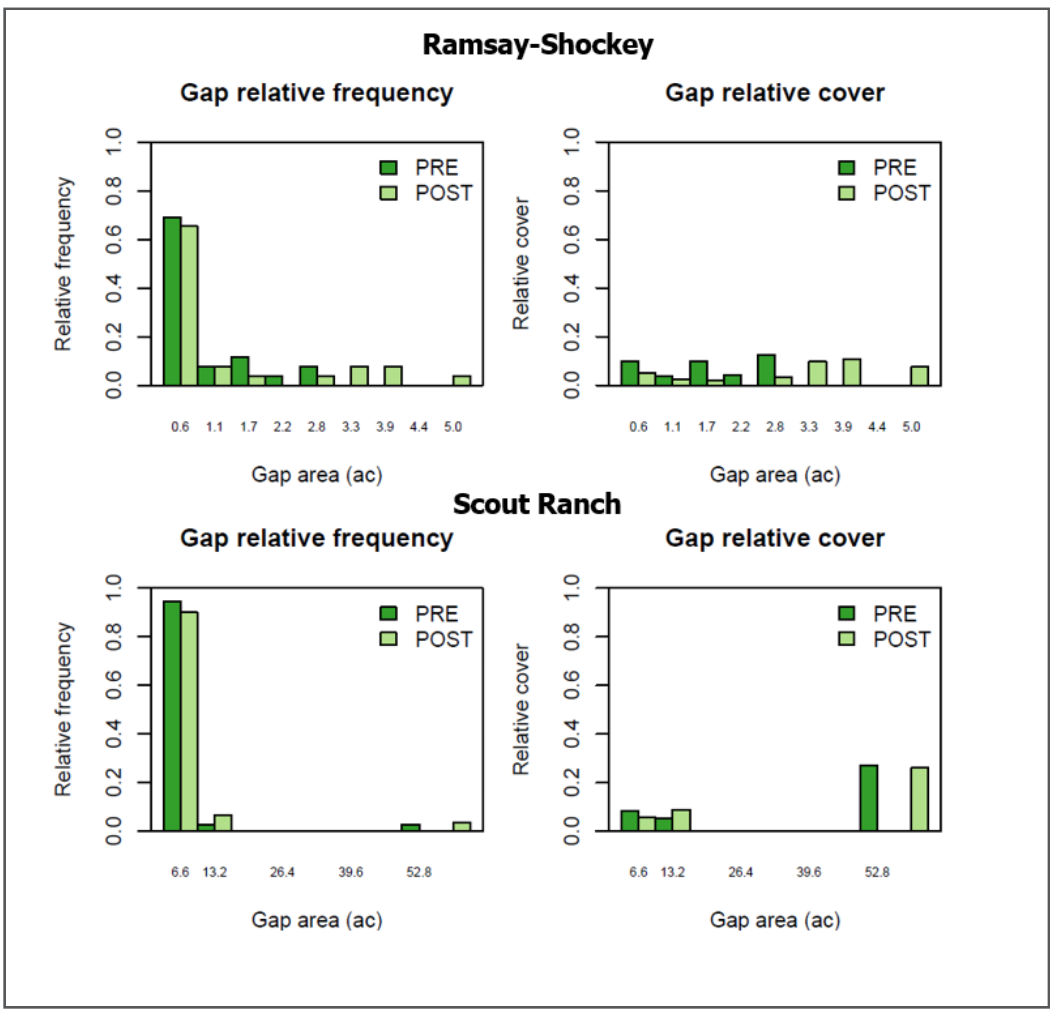

Figure 8: Gap distributions at Ramsay-Shockey (upper panels) and Scout Ranch units (lower panels) restoration treatment indicating shift in frequency (left panels) and cover (right panels) of gaps from primarily small gaps before treatments to increased dominance by larger gaps.

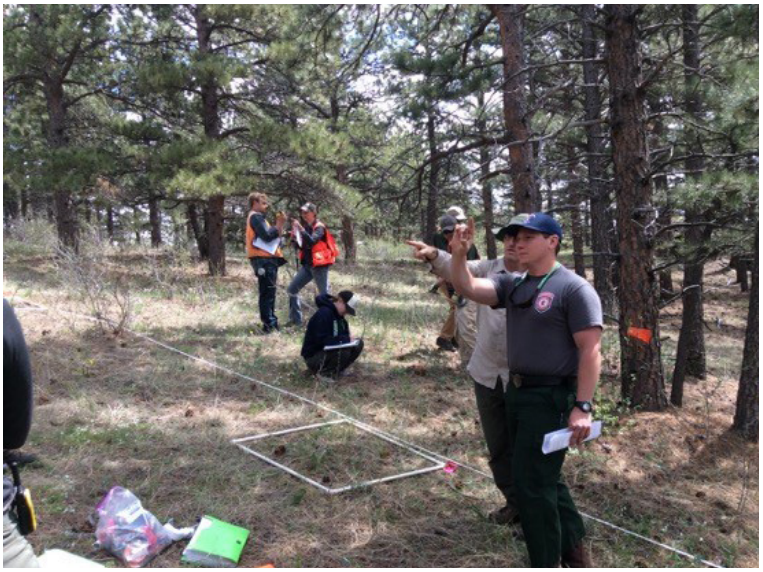

Figure 9: Colorado Forest Restoration Institute Assistant Director Brett Wolk assists a Colorado Division of Fire Prevention and Control firefighter with monitoring measurements at Ramsay-Shockey.

Ramsay-Shockey, CFRI hosted visitors from over 10 agencies and familiarized forestry and fire professionals with the monitoring process. The monitoring data collection process for this project was truly collaborative, as The Nature Conservancy and Coalition for the Poudre River Watershed regularly contributed to monitoring efforts at Scout Ranch. Other involved agencies included Colorado Division of Fire Prevention and Control, Bear Peak Wildland Fire module, Rocky Mountain Fire, the Colorado State Forest Service, Larimer County Open Space, and Redlands College and Colorado Natural Heritage Program student interns.

A number of natural resource-focused groups have also hosted field tours of the demonstration sites. The sites now provide an open-air forum to discuss the challenges and benefits of various management techniques. In 2017 and 2018, CFRI participated in field tours of Scout Ranch organized by the Northern Colorado Fireshed Network and Coalition for the Poudre River Watershed, as well as the multi-agency workshop introducing forest restoration concepts for the Front Range presented in RMRS-GTR-373 (Addington et al., 2018). These demonstration sites are also used to showcase restoration work that is occurring, and to engage local communities and potential investors in the Water Fund in a constructive exchange about forest restoration and watershed health.

Conclusion

Our analyses of modeled fire behavior suggest that Peaks to People forest restoration treatments enhanced forest resilience to wildfire within most management areas by changing conditions at demonstration sites to support low- to mixed-severity fire regimes. The combination of thinning followed by prescribed broadcast burning yielded the greatest reductions in fire hazard. Where tree density remained high in some areas of the Ramsay-Shockey site, additional treatments to decrease forest cover and increase frequency of larger gaps in the tree canopy could further improve forest health and resilience to future disturbances.

Acknowledgements

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Figure 10: Nature Conservancy landscape ecologist Rob Addington discusses monitoring protocols and forest management with Peaks to People stakeholders during data collection at Ramsay-Shockey.

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Appendix A: Monitoring Summaries

This Appendix contains individual summaries for each monitored stand, including pre- and post-treatment fuel conditions and predicted fire hazard based on field-collected data. We conducted fire modeling using the Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS). Fire weather and fuel moisture conditions used during severe and moderate fire simulations are recorded in Table 3 of the report.

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Monitoring Summary

Ben Delatour Scout Ranch—Burn Only

Wildfire Mitigation Strategy: Prescribed fire was applied to a ponderosa pine stand in a collaboratively funded demonstration project designed to promote forest resilience to wildfire and protect water supply and infrastructure.

Project Highlights: Prescribed fire reduced modeled fire hazard, achieving similar fire mitigation benefits as an adjacent unit that was mechanically thinned before prescribed burning. The fire reduced tree density and basal area, though some large ponderosa pine trees were killed in addition to smaller trees regularly targeted by fuels treatments. Crown base height of the remaining live trees raised substantially and surface fuels were reduced following the prescribed burn, which increased the stand's resistance to crown fire.

Project Information

Implementation Agency	The Nature Conservancy
Funding	The Nature Conservancy, Peaks to People Water Fund
Location	Larimer County, CO
Year Completed	2017
Area Monitored	5 acres
Forest Type	Ponderosa pine
Implementation Method	Broadcast burn
Slash Treatment	Broadcast burn


Pre-treatment photo point


Immediate post-burn photo point


1-year post-burn photo point

Forest and Fuels Inventory

Summary	**Pre-treatment**	**Post-treatment**
Year sampled	2017	2017
Live basal area* (ft^2/ac)	70 ± 40	36 ± 30
Live tree density (trees per acre)	104 ± 75	65 ± 70
Canopy cover (%)	37 ± 25	22 ± 25
Canopy base height (ft)	7 ± 4	33 ± 10
Fine Woody Fuel Loading (tons/acre)	0.68	0.37

*Basal area is the cross-sectional area of tree stems at breast height (4.5 ft.) for a given area.

Prescribed fire severity assessment

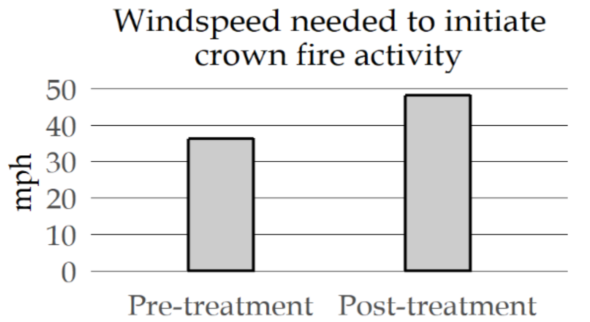
All five plots showed signs of fire, with 39% of plot ground surface visibly burned.

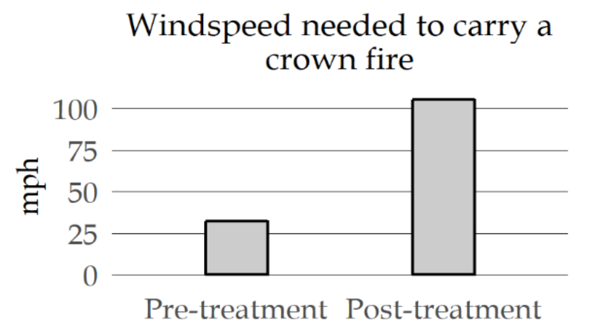
Fire Hazard Analysis

We assessed the effectiveness of fuels treatments to change expected fire behavior by collecting forest and fuels inventory data at 5 field plots pre-treatment and post-treatment. Field data was used to model potential fire behavior with the Fire and Fuels Extension to the Forest and Vegetation Simulator. The table displays fire behavior outputs modeled under severe and moderate conditions. The graph and images show changes in forest structure and modeled fire behavior under severe conditions.

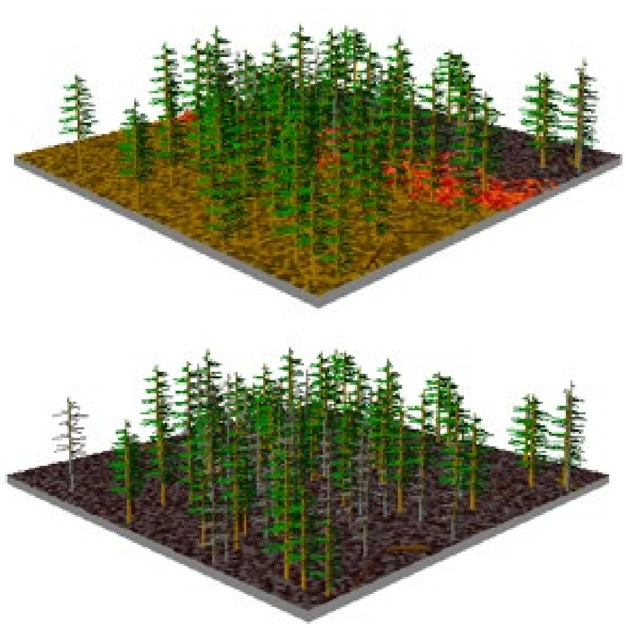
Modeled Fire Behavior

	Pre-treatment		**Post-treatment**	
Fire weather and fuel conditions	***Severe***	*Moderate*	***Severe***	*Moderate*
Fire type	Surface	Surface	Surface	Surface
Total flame length (ft)	2.8	1.2	6.2	0.2
Surviving tree basal area (ft^2/ac)	48 (68%)	56 (80%)	18 (50%)	28 (77%)





Pre-treatment



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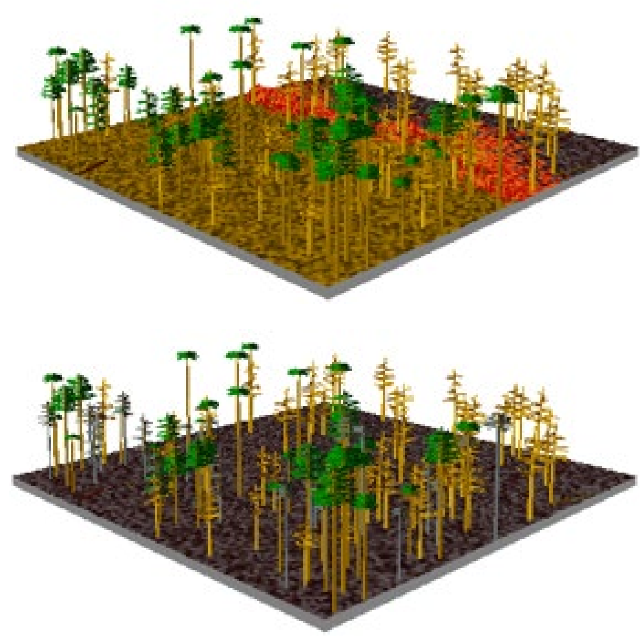

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Full methods and details described in the Peaks to People Monitoring Report, available at cfri.colostate.edu. January, 2019.

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Monitoring Summary

Ben Delatour Scout Ranch—Thin and Burn

Wildfire Mitigation Strategy: Mechanical thinning followed by a prescribed broadcast burn was applied to a ponderosa pine stand in a collaboratively funded demonstration project designed to promote forest resilience to wildfire and protect water supply and infrastructure.

Project Highlights: Fire hazard was relatively low before mitigation and was further reduced following the combined thin and burn treatment. Removing slash off site during mechanical thinning, and the subsequent prescribed burn, minimized surface fuel accumulations and raised average tree crown base height, improving resistance to torching and minimizing potential for active crown fire.


Pre-treatment photo point (2016)


Post-thin, pre-burn (2017)


Post-thin, post-burn (2017)


1-year post thin, post burn (2018)

Project Information

Implementation Agency	Coalition for the Poudre River Watershed, The Nature Conservancy
Funding	The Nature Conservancy, Peaks to People Water Fund, Coalition for the Poudre River Watershed
Location	Larimer County, CO
Year Completed	2017
Area Monitored	24 acres
Forest Type	Ponderosa pine
Implementation Method	Mechanical thin, broadcast burn
Slash Treatment	Removal, broadcast burn

Forest and Fuels Inventory

Summary	**Pre-treatment**	**Post-thin**	**Post-thin, post-burn**
Year sampled	2016	2017	2018
Live basal area* (ft²/ac)	69 ± 34	30 ± 25	31 ± 25
Live tree density (trees per acre)	97 ± 63	39 ± 47	39 ± 47
Canopy cover (%)	38 ± 20	26 ± 22	26 ± 19
Canopy base height (ft)	12 ± 7	9 ± 5	14 ± 10
Fine Woody Fuel Loading (tons/acre)	1.22	1.19	1.17

*Basal area is the cross-sectional area of tree stems at breast height (4.5 ft) for a given area.

Prescribed fire severity assessment

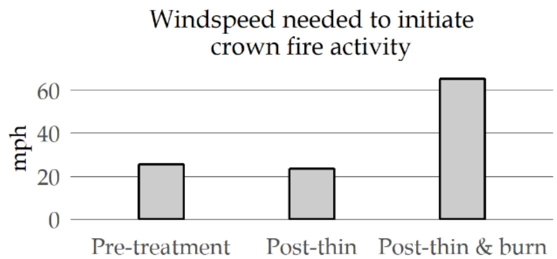
The prescribed fire was extensive but patchy, with eight of thirteen plots showing signs of fire, but only 23% of ground surface visibly burned.

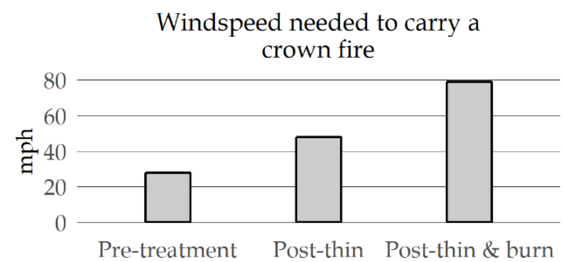
Fire Hazard Analysis

We assessed the effectiveness of fuels treatments to change expected fire behavior by collecting forest and fuels inventory data at 13 field plots pre-treatment and post-treatment. Field data was used to model potential fire behavior with the Fire and Fuels Extension to the Forest and Vegetation Simulator. The table displays fire behavior outputs modeled under severe and moderate conditions. The graph and images show changes in forest structure and modeled fire behavior under severe conditions.

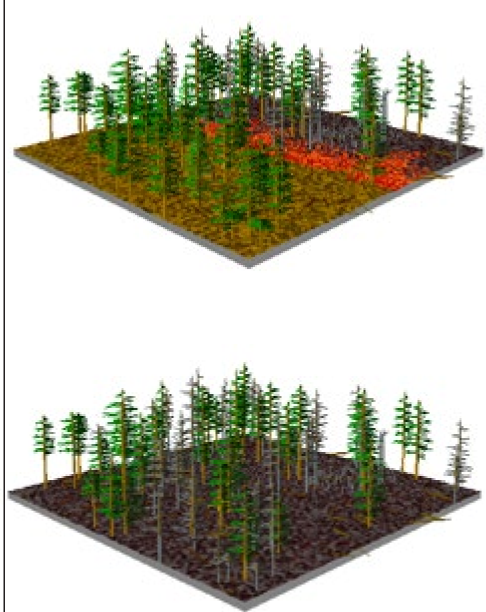
Modeled Fire Behavior

	Pre-treatment		**Post-thin**		**Post-burn**	
Fire weather and fuel conditions	*Severe*	*Moderate*	*Severe*	*Moderate*	*Severe*	*Moderate*
Fire type	Surface	Surface	Surface	Surface	Surface	Surface
Total flame length (ft)	3.8	1.6	3.7	1.4	3.6	1.4
Surviving tree basal area (ft^2/ac)	39 (56%)	56 (81%)	21 (70%)	25 (82%)	24 (77%)	26 (83%)

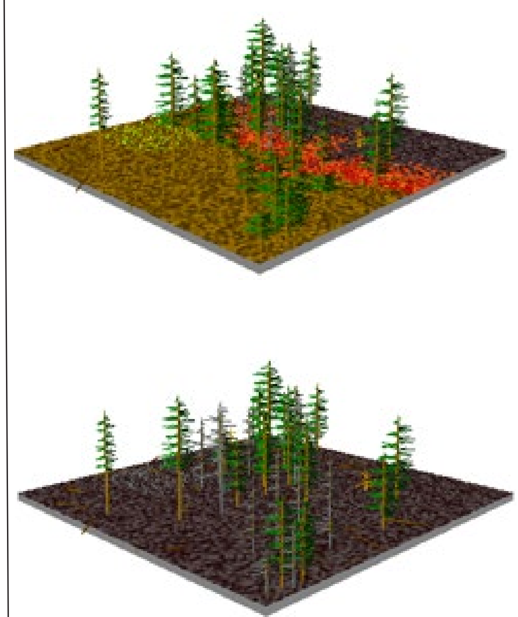




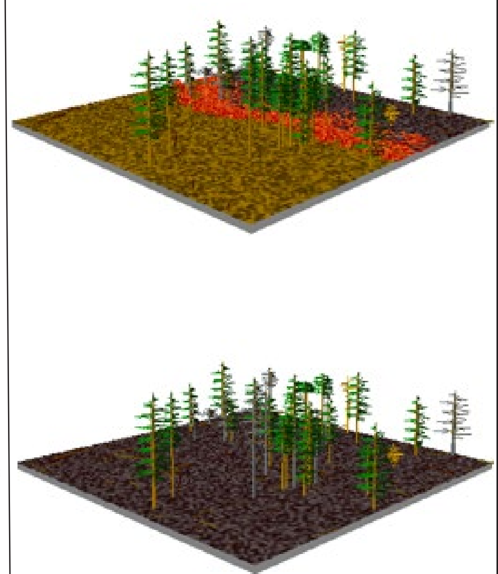
Pre-treatment



Post-Thin



Post-Thin & Burn



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Full methods and details described in the Peaks to People Monitoring Report, available at cfri.colostate.edu. January, 2019.

Monitoring Summary

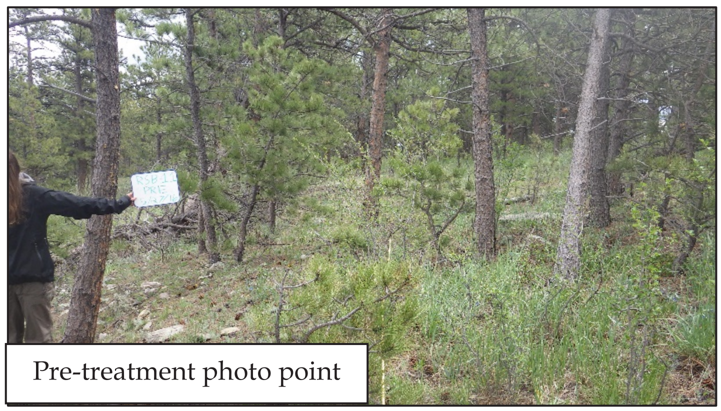
Ramsay Shockey Unit B

Wildfire Mitigation Strategy: Ponderosa pine was thinned, with residual slash pile burned in a collaboratively funded demonstration project designed to promote forest resilience to wildfire and protect water supply and infrastructure.

Project Highlights: Forest thinning created larger gaps in the tree canopy that lowered the potential for active crown fire spread. Residual slash was placed into piles for burning, which resulted in a reduction of fine woody surface fuels across the unit. However, predicted tree mortality under severe fire conditions remains relatively high. Follow-up maintenance activities, such as broadcast burning, could further reduce surface fuel loading, raise tree crown base height, and generally extend benefits of fire mitigation.

Project Information

Lead Implementer	Larimer County Department of Natural Resources
Funding Sources	Peaks to People Water Fund, Northern Water
Year Completed	2016
Area Monitored	21 acres
Forest Type	Ponderosa pine
Implementation Method	Hand thin
Slash Treatment	Pile burn



Pre-treatment photo point

Forest and Fuels Inventory

Summary	Pre-treatment	1 yr post-treatment
Year sampled	2016	2017
Live basal area* (ft^2/ac)	79 ± 53	46 ± 32
Live tree density (trees per acre)	174 ± 149	75 ± 72
Canopy cover (%)	37 ± 22	30 ± 25
Canopy base height (ft)	10 ± 5	11 ± 5
Fine Woody Fuel Loading (tons/acre)	1.2	0.8

* Basal area is the cross-sectional area of tree stems at breast height (4.5 ft) for a given area.

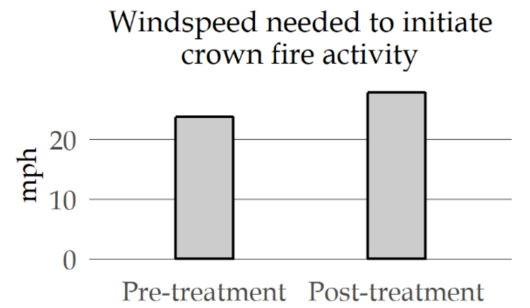
Post-treatment photo point

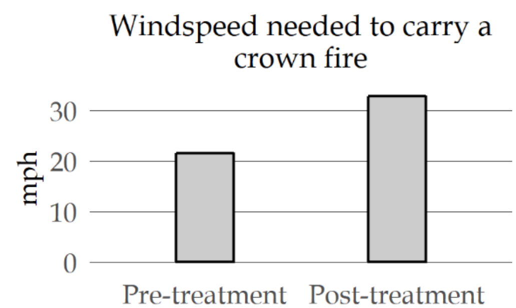
Fire Hazard Analysis

We assessed the effectiveness of fuels treatments to change expected fire behavior by collecting forest and fuels inventory data at 11 field plots pre-treatment and post-treatment. Field data was used to model potential fire behavior with the Fire and Fuels Extension to the Forest and Vegetation Simulator. The table displays fire behavior outputs modeled under severe and moderate conditions. The graph and images show changes in forest structure and modeled fire behavior under severe conditions.

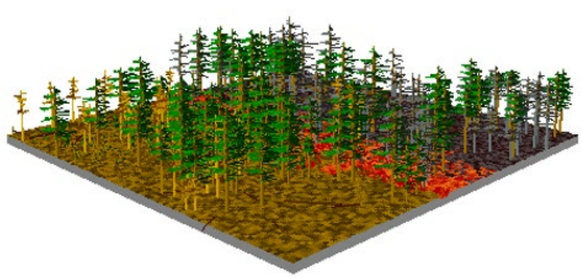
Modeled Fire Behavior

	Pre-treatment		**1 yr post-treatment**	
Fire weather and fuel conditions	***Severe***	*Moderate*	***Severe***	*Moderate*
Fire type	Surface	Surface	Surface	Surface
Total flame length (ft)	3.5	1.5	3.9	1.6
Surviving tree basal area (ft^2/ac)	32 (40%)	60 (76%)	22 (47%)	36 (78%)





Pre-treatment



Post-Treatment

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Monitoring Summary

Ramsay Shockey Unit C

Wildfire Mitigation Strategy: Ponderosa pine was thinned, with residual slash lopped and scattered in a collaboratively funded demonstration project designed to promote forest resilience to wildfire and protect water supply and infrastructure.

Project Highlights: Forest thinning decreased tree density by almost half, but only reduced basal area slightly as a result of focusing on the removal of small trees. Predicted fire hazard mitigation benefits were minimal following treatment. While thinning increased modeled windspeeds needed to carry active crown fire in the stand due to more space between tree crowns, lower windspeeds are predicted to initiate tree torching, flame lengths remain high, and fewer trees are predicted to survive a wildfire. Additional tree removal combined with slash treatment to reduce surface fuels, such as broadcast burning, may increase fuels reduction benefits and enhance stand resilience to wildfire.

Project Information

Lead Implementer	Larimer County Department of Natural Resources
Funding Sources	Peaks to People Water Fund, Northern Water
Location	Larimer County, CO
Year Completed	2016
Area Monitored	34 acres
Forest Type	Ponderosa pine
Implementation Method	Hand thin
Slash Treatment	Lop and scatter

Pre-treatment photo point

Forest and Fuels Inventory

Summary	**Pre-treatment**	**1 yr post-treatment**
Year sampled	2016	2017
Live basal area* (ft^2/ac)	116 ± 35	90 ± 38
Live tree density (trees per acre)	257 ± 165	143 ± 70
Canopy cover (%)	52 ± 8	42 ± 13
Canopy base height (ft)	13 ± 5	13 ± 7
Fine Woody Fuel Loading (tons/acre)	0.7	1.4

* Basal area is the cross-sectional area of tree stems at breast height (4.5 ft) for a given area.

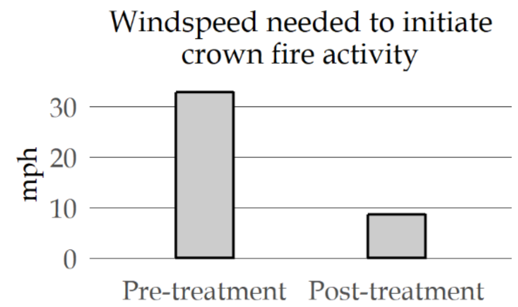
Post-treatment photo point

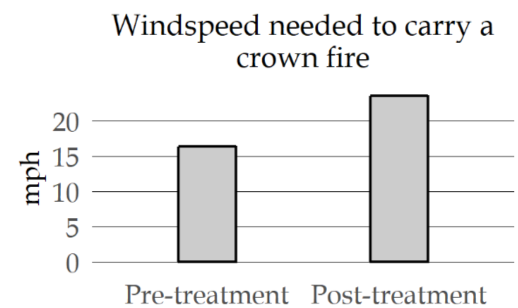
Fire Hazard Analysis

We assessed the effectiveness of fuels treatments to change expected fire behavior by collecting forest and fuels inventory data at 9 field plots pre-treatment and post-treatment. Field data was used to model potential fire behavior with the Fire and Fuels Extension to the Forest and Vegetation Simulator. The table displays fire behavior outputs modeled under severe and moderate conditions. The graph and images show changes in forest structure and modeled fire behavior under severe conditions.

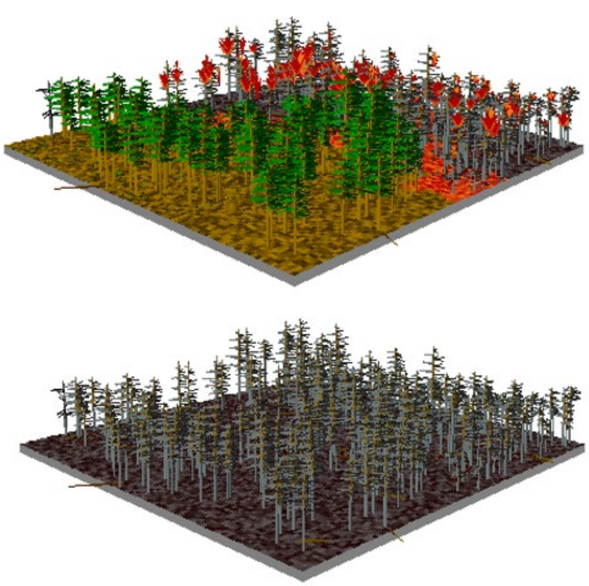
Modeled Fire Behavior

	Pre-treatment		1 yr post-treatment	
Fire weather and fuel conditions	*Severe*	*Moderate*	*Severe*	*Moderate*
Fire type	Conditional Crown	Surface	Passive	Surface
Total flame length (ft)	42.1	1.5	30.0	3.1
Surviving tree basal area (ft^2/ac)	0 (0%)	87 (75%)	1 (1%)	57 (63%)

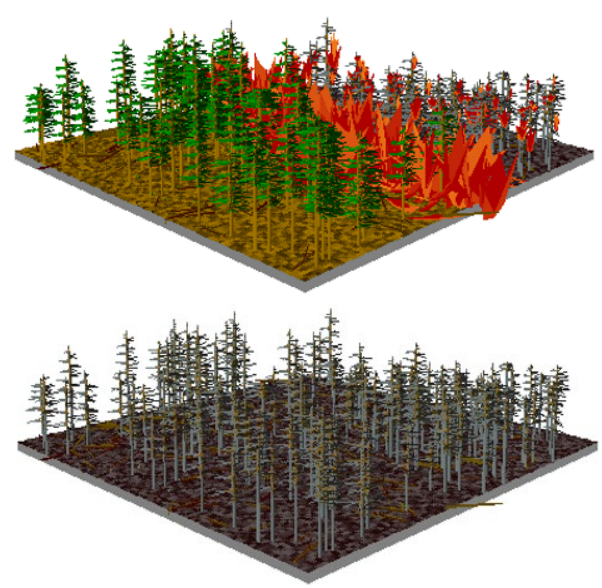




Pre-treatment



Post-Treatment



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