Developing Tools and Processes to Inform Forest Plan Monitoring and Evaluation:

A report to the Pike and San Isabel National Forests Cimarron and Comanche National Grasslands

January, 2021

CFRI - 2101

COLORADO FOREST RESTORATION INSTITUTE

FOREST AND RANGELAND STEWARDSHIP
COLORADO STATE UNIVERSITY

Colorado Forest Restoration Institute

The Colorado Forest Restoration Institute (CFRI) was established in 2005 as an application-oriented, 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. Along with centers at Northern Arizona University and New Mexico Highlands University, CFRI is one of three Institutes that make up the Southwest Ecological Restoration institutes, which were authorized by Congress through the Southwest Forest Health and Wildfire Prevention Act of 2004. We lead collaborations between researchers, managers, and stakeholders to develop, synthesize, and apply locally-relevant, actionable knowledge to inform forest management strategies and achieve wildfire hazard reduction goals in Colorado and the Interior West. 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. We do this through collaborative partnerships involving researchers, forest land managers, interested and affected stakeholders, and communities.

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Glossary of terms

Term	Acronym	Description
Burn probability		The annual likelihood of encountering wildfire at a given location on the landscape.
Common Stand Exam	CSE	USDA Forest Service program that collects standard forest inventory data to characterize forest stand conditions.
Conditional net value change	cNVC	The anticipated change in a resource or asset value when exposed to wildfire. cNVC is quantified for each resource and asset by combining spatial data on its extent with flame length predictions and relative response functions that specify the direction and magnitude of change predicted for each level of fire intensity.
Conservation Easement Assessment Project Coupled Model	CEAP	A model framework which simulates the effects of hazardous fuels reduction and ecological restoration treatments on ecological outcomes related to forest structure, wildfire hazard and behavior, and post-fire soil erosion.
Crown fire activity		Measure of expected fire behavior resulting from a combination of fuel model, stand height, crown base height, and crown bulk density.
Effects analysis		Analysis of a highly valued resource and asset's (HVRA) susceptibility to fire. Within a Quantitative Wildfire Risk Assessment, typically the susceptibility of HVRAs to varying levels of fire intensity (Scott et al. 2013).
Expected net value change	eNVC	The product of the Conditional net value change (cNVC) and burn probability resulting in wildfire risk to a HVRA.
Fireline intensity		The product of the rate of spread and heat generated from the available fuel during flaming combustion. The primary unit is British Thermal Unit per second per foot (Btu/sec/ft) of fire front (Byram 1959).
Flame length		The distance from the midpoint of the active flaming front to the average tip of the flames (Andrews 2009).
FlamMap		Wildfire mapping and analysis computer software program that simulates potential fire behavior characteristics including: spread rate, flame length, fireline intensity, etc., as well as fire growth and spread, and conditional burn probabilities under constant weather and fuel moisture conditions (Finney et al. 2015).
Forest Inventory and Analysis	FIA	USDA Forest Service program that collects, analyzes, and reports information on the condition and health of forests as well as trends in US forests on an annual basis.
FragStats		A computer software program that computes a wide variety of spatial landscape metrics for quantifying the structure (composition and configuration) of landscapes (McGarigal et al. 2012).
Hazard assessment		Landscape assessment of wildfire hazard where wildfire occurrence and spread are simulated in order to characterize how variation in weather conditions and spatial variability in fuel, topography and ignition density influence wildfire likelihood across a landscape (Scott et al. 2013).
Highly Valued Resources and Assets	HVRA	Values-at-risk related to resources such as human life safety, critical infrastructure, water supply, wildland-urban interface, wildlife, and recreation, etc. as determined by local resource experts and stakeholders.
LANDFIRE		Nationally consistent geospatial products and databases of 30-m resolution vegetation, wildland fuel, and wildfire regime data across the United States that can be used to inform strategic fire and resource management planning and analysis.

Potential control locations	PCL	Locations where wildland fires are likely to be stopped.
Potential wildfire operational delineations	PODs	Strategic planning tool developed collaboratively with local expertise and advanced spatial analysis that identifies areas of risk and/or opportunities used to contain a wildfire in order to assist in integrating land management objectives and wildfire incident response.
Quantitative Wildfire Risk Assessment	QWRA	A quantitative framework for assessing wildland fire risk to highly valued resources and assets (HVRA) where risk is a function of wildland fire hazard and HVRA vulnerability (Scott et al. 2013).
Risk Assessment for Priority Investment Decision Support	RAPIDS	A modeling framework that uses science-based methods to prioritize fuels treatments to maximize return on investment
Revised Universal Soil Loss Equation	RUSLE	Predicts long-term, average annual soil loss in Mg ha-1 yr-1 as the product of rainfall erosivity, soil erodibility, length and slope, cover, and support practices for a broad range of farming, conservation, mining, construction, and forestry uses (Renard et al. 1997).
Strategic Response Zones	SRZs	A mapped location that delineates an ecologically-based strategic response to wildland fire, such as protect, restore, or maintain, or an operational response to wildland fire, such as full suppression, confine, point or zone protection, monitor.
Suppression difficulty Index	SDI	Spatial location of potential hazards and/or reduced risk to firefighters, such as potential fire behavior or accessibility, that can be used to assess the relative suppression effort and also to facilitate strategic and tactical fire management decisions.
Wildland Urban Interface	WUI	Transition zone where human development encroaches upon and intermixes with wildland vegetation. Communities within the WUI are at increased risk of catastrophic wildfire.

Executive Summary

The Colorado Forest Restoration Institute (CFRI) at Colorado State University is engaged in a cooperative agreement with the Arapaho-Roosevelt National Forests and Pawnee National Grassland (ARP) and Pike and San Isabel National Forests Cimarron and Comanche National Grasslands (PSICC) to provide science support to improve data integration across the Front Range forests, and develop tools and processes to facilitate applying monitoring data to inform Forest Plan Monitoring and Evaluation.

The report herein focuses on progress related to two objectives of the cooperative agreement with the PSICC, which are as follows:

1) Assess and report on tools and methods to link project-scale monitoring of forest vegetation management projects and Forest Plan-scale monitoring components (forest structure and composition; wildfire behavior and effects; post-wildfire soil loss) under the 2012 National Forest Planning Rule

2) Develop, apply, and report on strategies for CFRI to serve as a clearinghouse for ecological monitoring data to feed into Forest Plan Monitoring reviews and adaptive management.

In section 1, we describe the ways in which four spatial analytical decision support tools may inform assessment, planning, and monitoring under the 2012 Planning Rule related to the components in objective 1 above. Developing spatially-explicit management plans, priority investments, and monitoring results can help managers illustrate changes and outcomes, as well as determine whether investments are worthwhile. The spatial tools that we reviewed are the Conservation Effects Assessment Project (CEAP) coupled modeling framework, Quantitative Wildfire Risk Assessment (QWRA), fuel treatment prioritization utilizing a risk analysis for priority investment decision support framework (RAPIDS), and pre-season wildfire response planning using potential wildfire operational delineations (PODs). See Table 1 for a summary of each tool, use in Forest planning, advantages, and limitations.

We found that these tools were applied in different forest assessment, planning, and monitoring contexts, and have unique advantages and limitations that must be considered in relation to local needs and priorities. Also, the decision support tools described herein are not mutually exclusive. There is considerable overlap between them, and there are opportunities to integrate tools to support Forest planning as appropriate.

The analytical tools described herein each use LANDFIRE for baseline vegetation and fuel layers. Employing common datasets in the assessment, planning, and prioritization phases of Forest Plan revision provides an opportunity to develop quantifiable desired conditions and other plan components which can be used to monitor progress in moving the forest towards desired conditions and meeting Plan goals and objectives. LANDFIRE layers can be augmented at regular intervals to assess the effects of treatment outcomes on forest-level conditions. Yet, the extent to which treatment outcomes can inform modeling of landscape-scale desired conditions depends in part on the type, resolution, and quality of monitoring data and local- and regional- level capacity and investment in monitoring programs.

In Section 2, we provide an overview of the monitoring projects CFRI manages. The purpose was to document what data CFRI collects and where, assess comparability to other related and relevant monitoring programs and sources (Forest Inventory and Analysis (FIA), common stand exam (CSE)), inform potential future monitoring efforts, and identify relevant datasets CFRI may house as a clearinghouse for ecological data (Objective 2).

The development of this report was iterative and informed by multiple meetings with the PSICC planner and several staff, which has resulted in a number of spin-off projects and next steps that may facilitate future cooperative work agreements to inform Forest Plan revision (currently scheduled for 2024 on the PSI):

- We worked with the PSICC forest planner to co-develop and submit a proposal to the Regional Office for funding to develop a Forest-wide assessment using the RAPIDS framework. Although the proposal was not funded, we will continue to search for additional funds or ways to leverage funds and support this project. The South Platte Ranger District is initiating an Environmental Assessment for a proposed vegetation management project, and the District Ranger has expressed interest in applying some of the tools described herein to inform that process.
- Developed and deployed a pilot questionnaire to identify the highest priority data and information needs to support decision-making related to planning and monitoring. We piloted this questionnaire with seven resources specialists, which were selected by the Forest Planner and Natural Resources Staff Officer at the PSICC. We intend to present preliminary findings to the PSICC Planning and Renewable Resources group in Spring 2021 in an open session with other resource specialists and personnel to identify next steps.
- CFRI is in the process of developing a CFRI Geospatial Portal, a spatial data portal and map viewing platform to help inform management decisions at multiple scales. In that vein, we intend to develop a planning data section, with spatial data that directly informs Forest Plan revision, biennial monitoring and evaluation reporting, and landscape-scale planning efforts for the Arapaho Roosevelt and Pike San Isabel National Forests. The needs assessment pilot described above is the first step in identifying types of data the PSICC uses for planning and monitoring, limitations of such data, and additional data and information needs to better integrate best available science and information into Forest planning and monitoring. Continued collaboration with the Forest Planner and PSICC Planning and Renewable Resources group will be necessary to build off initial findings and develop a geospatial portal that is useful and useable.

Introduction

The Colorado Forest Restoration Institute (CFRI) at Colorado State University is engaged in a cooperative agreement with the Arapaho-Roosevelt National Forests and Pawnee National Grassland (ARP) and Pike and San Isabel National Forests Cimarron and Comanche National Grasslands (PSICC) to provide science support to improve data integration across the Front Range forests, and develop tools and processes to facilitate applying monitoring data to inform Forest Plan Monitoring and Evaluation (17-CS-11021000-032, Project 5).

The report focuses on progress related to objectives 1 and 2 of the cooperative agreement, which are as follows:

1. Assess and report on tools and methods to link project-scale monitoring of forest vegetation management projects and the following Forest Plan-scale monitoring components under the 2012 National Forest Planning Rule:
   a) Restoring and sustaining ecological integrity of forest vegetation structure and composition;
   b) Reducing unwanted wildfire and promoting desired fire behavior and effects;
   c) Enhancing the resilience and sustainability of source-water resources through reducing soil loss from high-severity wildfire.
2) Develop, apply, and report on strategies for CFRI to serve as a clearinghouse for ecological monitoring data to feed into Forest Plan Monitoring reviews and adaptive management.

Report outline and link to objectives

In this report, we build upon previous cooperative agreements with the ARP[1] and PSICC[2]. In the first section, we identify the ways in which four spatial analytical decision support tools can inform assessment, planning, and monitoring under the 2012 Planning Rule, focusing specifically on forest structure and composition, wildfire risk, and post-fire soil erosion (Objective 1). As applicable, we review how other National Forests have used these tools in Plan revision. Employing common datasets in the assessment, planning, and prioritization phases of Forest Plan revision provides an opportunity to develop quantifiable desired conditions and other plan components which can be used to monitor progress in moving the forest towards desired conditions and meeting Plan goals and objectives. This section also addresses current limitations to linking treatment-level data to Forest Plan components.

In section 2, we document the monitoring projects that CFRI manages, and other potentially relevant monitoring projects and sources, both inside and outside the PSICC (e.g., Forest Inventory and Analysis (FIA), common stand exam (CSE)). We included what metrics are collected, what questions they address, and how they are analyzed in order to assess comparability across projects, inform future monitoring efforts, and identify relevant and appropriate datasets to house at CFRI (Objective 2). In the discussion, we describe program of work refinements and next steps based on multiple meetings with PSICC staff as the unit gears up for Forest Plan revision (currently scheduled for 2024).

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1 Cannon et al. 2019- https://cfri.colostate.edu/wp-content/uploads/sites/22/2019/08/ARP_Final_Report.pdf This report provided guidance on current ecological monitoring efforts conducted through the Front Range Collaborative Forest Landscape Restoration Program (CFLRP), 2) demonstrated application of these efforts to ARP forest plan monitoring, and 3) discussed advantages and limitations of current and potential monitoring efforts, as well as remaining needs. See also the full report at https://cfri.colostate.edu/wp-content/uploads/sites/22/2019/08/2018-ARP_REPORT_20180105.pdf

2 Cannon et al. 2019 - https://cfri.colostate.edu/wp-content/uploads/sites/22/2019/08/Cannon_et_al_PSICC_landscape_analysis_FinalReport.pdf – This report introduced a coupled modeling framework for simulating management strategies and analyzing their implications for forest structural heterogeneity, wildfire impacts, and post-fire erosion risk mitigation. The Outputs from these tools have potential applications for forest plan revision, landscape scale NEPA, treatment design, and the achievement of Shared Stewardship goals for outcome-based and collaborative restoration and risk reduction.

Section I: Assessing the utility of CFRI spatial analytical decision support tools in supporting Forest Planning

Introduction

CFRI has developed and supported the development of several spatial analytical decision support tools that may be relevant to Forest planning. Here, we first briefly discuss the components of the 2012 Forest Planning Rule. We then introduce four related spatial analytical decision support tools CFRI deploys to assist partners in assessment and planning. These include a Conservation Effects Assessment Project (CEAP) coupled modeling framework, Quantitative Wildfire Risk Assessment (QWRA), fuel treatment prioritization utilizing a risk analysis for priority investment decision support framework (RAPIDS), and pre-season wildfire response planning using potential wildfire operational delineations (PODs). For each tool, we describe some ways in which they can be employed in the assessment, planning and prioritization, and monitoring phases of Forest Plan revision and implementation, along with some advantages and limitations of each.

We focus on tools that address forest components of relevance to our PSICC and CFRI cooperative agreement, including:

i) Restoring and sustaining ecological integrity of forest vegetation structure and composition

ii) Reducing unwanted wildfire and promoting desired fire behavior and effects.

iii) Enhancing the resilience and sustainability of source-water resources through reducing soil loss from high-severity wildfire.

The tools that we describe below and their utility in informing Forest Plan assessment, planning, and monitoring is informed by multiple conversations over several months among CFRI staff and PSICC personnel. Where applicable, we reviewed Forest Plans and the required Environmental Impact Statements where these spatial analytical tools were deployed for Forest Plan revision.

2012 Planning Rule Context

Under the Planning Rule, assessment, planning, and monitoring operate in a continuous feedback loop, and thus one should inform the other. During the assessment phase, the responsible official is required to evaluate existing information on 15 topic areas, including assessment of key ecological characteristics of ecological integrity and the ways in which stressors (e.g., wildfire, climate change) impact the Plan area. Current ecosystem conditions are evaluated against departure from historical or desired conditions, or a suitable alternative. In the planning phase, the assessment is used to identify the need for change, identify plan components (e.g., desired conditions, standards and guidelines), delineate priority watersheds for restoration, and support the analysis of plan alternatives under the National Environmental Policy Act. The Planning rule requires monitoring to "inform the management of resources on the plan areas, including by testing relevant assumptions, tracking relevant changes and measuring management effectiveness and progress toward achieving or maintaining the plan's desired conditions or objectives" (36 CFR 219.12 [a] [2]). Biennial monitoring and evaluation reports are required under the 2012 Planning rule. These reports allow managers to evaluate the implementation of plan components and determine whether a change is needed to the monitoring question, indicator, or plan components.

CFRI Spatial Products

Here, we introduce four related decision support tools that CFRI employs, identify the ways in which each approach has or may inform phases of Forest planning, and document advantages and limitations of each approach (See Table 1 for a summary of findings). These approaches are not mutually-exclusive, and there is a great deal of overlap and potential for integration among them, depending on needs and priorities. The CEAP model, QWRA, and fuel treatment prioritization models all use LANDFIRE for baseline layers. LANDFIRE is an important dataset for landscape-scale forest restoration and fuel management planning. It is a nationally consistent, "all-lands," 30-meter resolution dataset. It was specifically designed to model fire behavior, and includes disturbance, vegetation, fuel, fire regime, topographic, and seasonal products to support landscape assessment, analysis, and management. A major advantage to using consistent baseline layers across modular modeling products is that it provides a common framework with which to identify quantifiable desired conditions and evaluate the ways in which forest management actions are moving the plan area towards desired conditions through iterative updates to the model as conditions change (e.g., treatments, wildfire). LANDFIRE allows users to augment fuels layers as new spatial implementation monitoring data is available, and thus provides an opportunity to iteratively assess treatment-level and cumulative restoration effects on forest conditions.

Conservation Effects Assessment Project Coupled Model

Cannon et al. (2019a, 2020) developed a model framework which simulates the effects of hazardous fuels reduction and ecological restoration treatments on ecological outcomes related to forest structure, wildfire hazard and behavior, and post-fire soil erosion (Figure 1 – hereafter referred to as CEAP). The model specifications, components, and analysis capabilities can be found in Cannon et al. (Cannon et al. 2019b) and was introduced in partial fulfillment of a FY19 PSICC/CFRI modification to the cooperative agreement, so we only briefly outline here. The effects of treatments on forest condition are simulated using baseline fuels layers (LANDFIRE), empirical outcomes (e.g., mean treatment effect), historical or desired conditions, and soil moisture. The resulting layers derived from the simulations can then serve as inputs to ecological process models (e.g., FragStats, FlamMap, Revised Universal Soil Loss Equation (RULSE)) to estimate ecological outcomes related to forest structure and heterogeneity, fire hazard and behavior, and post-fire soil erosion (Figure 1). Additional process models can be incorporated into this modular framework to address other management resources of concern, as appropriate and available.

Although this framework has not yet been incorporated into a formal planning process, CEAP has several utilities for planning at multiple scales:

Assessment – Analysis of existing conditions, simulated conditions, and model outputs can be used to characterize departure from existing conditions. LANDFIRE can be used to derive existing conditions

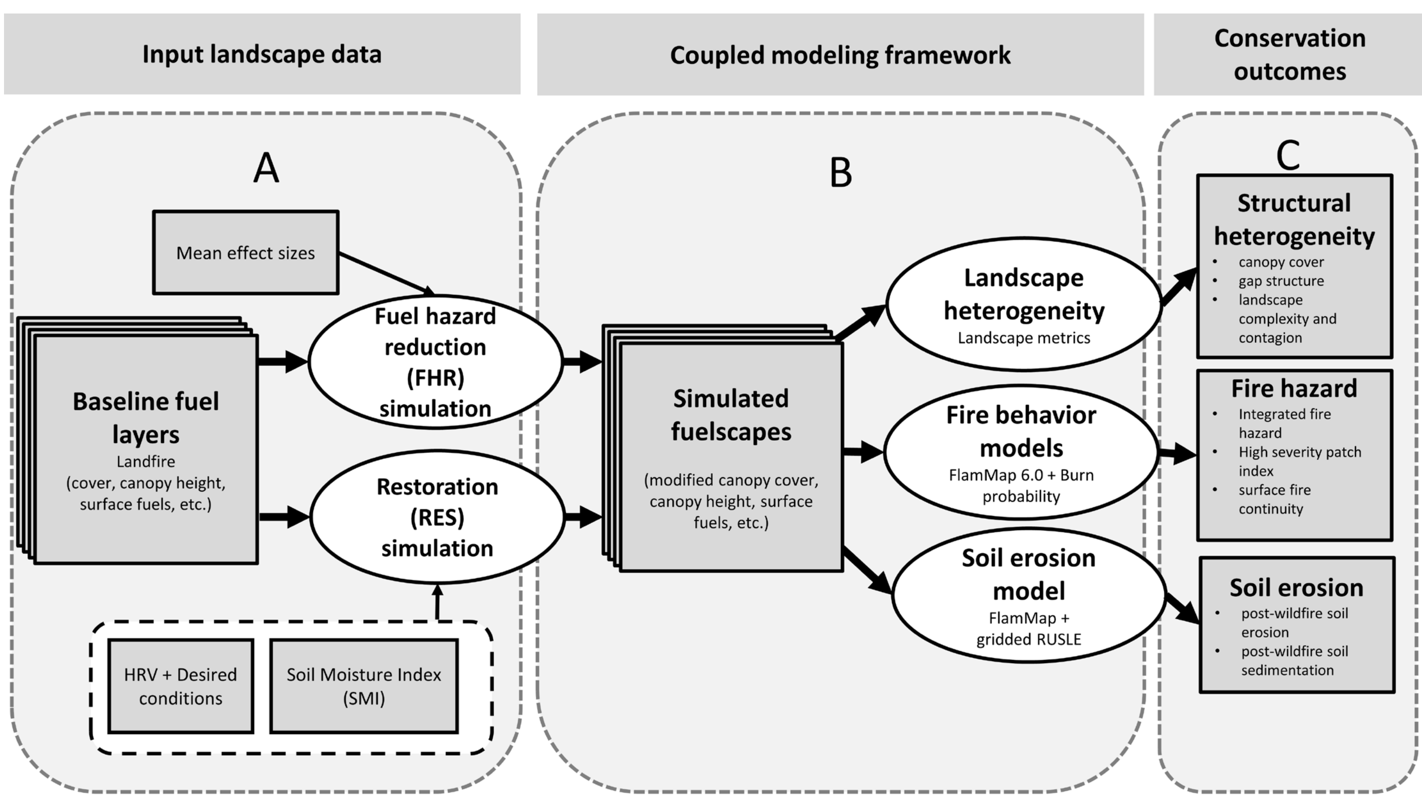

Figure 1: CEAP Coupled model framework. Source: Cannon et al. 2020.

Table 1: Summary table of spatial analytical models for decision-support used by CFRI.

For each model, we include a description of the approach, it's utility in different phases of forest planning, advantages, and limitations. We also indicate which components of interest to the cooperative agreement are addressed by each model: i) Restoring and sustaining ecological integrity of forest vegetation structure and composition; ii) Reducing unwanted wildfire and promoting desired fire behavior and effects; iii) Enhancing the resilience and sustainability of source-water resources through reducing soil loss from high-severity wildfire.

	Conservation Effects Assessment Program (CEAP) coupled model	**Quantitative Wildfire Risk Assessment (QWRA)**	**Fuel treatment prioritization (RAPIDS)**	**Potential operational delineations (PODs)**
Description	Simulates effects of fuels reduction/restoration treatments on forest structure, wildfire hazard and behavior, and soil erosion	Combines fire behavior modeling with local knowledge to determine the susceptibility of Highly Valued Resources and Assets (HVRAs) to wildfire	Prioritize optimal treatment strategies under treatment cost, feasibility, and budget constraints to maximize wildfire risk reduction	Integrates fire modeling products (suppression difficulty; potential control locations) and local knowledge to identify landscape areas and features most likely to contain wildfire.
Forest components of interest to cooperative agreement	i, ii, iii	ii, iii	ii, iii	
Assessment	Existing conditions derived from LANDFIRE (no-treatment scenario) and compared to simulated conditions (treated landscape) of historical/ desired conditions	Southern Sierra QWRA supported Forest Plan Revision on R5 National Forests	Uses QWRA	Uses QWRA
Planning/Prioritization	Supports development of optimal treatment to meet desired conditions; Useful for alternative development and implementation flexibility	Delineate strategic wildfire management areas, each with unique desired conditions, goals, standards, and guidelines.	Supplement QWRA to define optimal treatment strategies to maximize wildfire risk reduction	Delineate Strategic Response Zones (SRZs), each with unique desired conditions, goals, standards, and guidelines; Alternative development - focal landscapes to match scale of restoration with wildfire behavior

	Conservation Effects Assessment Program (CEAP) coupled model	Quantitative Wildfire Risk Assessment (QWRA)	Fuel treatment prioritization (RAPIDS)	Potential operational delineations (PODs)
Monitoring	Spatial implementation monitoring data used to alter fuel models and re-run model (i.e., modeled change in forest health and resilience)	Acres burned by objective; spatial implementation monitoring data used to alter fuel models and re-run model (i.e., change in risk); Change in proportion of plan area in strategic wildfire management area	Assess amount of risk reduction relative to investment – Return on Investment (ROI) in meeting desired conditions	Number and acres of fire managed for resource benefit; Proportion of forest in SRZ categories
Advantages	Explicitly simulates treatment effects to ecological integrity, wildfire risk, soil erosion; Flexible scenario-based approach	Leverage and refine 2019 QWRA effort on PSI and RO efforts; Assesses wildfire risk to locally-relevant priorities; collaborative process for participatory model exploration and development	Interfaces with QWRA; supports ROI planning; collaborative process for participatory model exploration and development	Interfaces with QWRA; PODs demarcated for PSI in 2019; PODs Atlas prototype summarizes geospatial data – i.e., useful as "clearinghouse" of spatial data for planning
Limitations	Does not include treatment constraints, or wildfire risk to HVRAs; lacking explicit incorporation of climate change risk/vulnerability	Doesn't incorporate natural range of variation, or structural heterogeneity; Defining desired conditions challenging due to social and ecological context of wildfire risk; lacking explicit incorporation of climate change risk/vulnerability	Doesn't incorporate natural range of variability or structural heterogeneity analysis; cost estimates are relative; lacking explicit incorporation of climate change risk/vulnerability	Integration with QWRA required for Strategic Response Zone delineation; Some resource specialists hesitant to use PODs for non-fire land and resource management objectives; lacking explicit incorporation of climate change risk/vulnerability

(e.g., a no treatment scenario). Simulated treatments are then used to develop desired or reference landscape conditions. The difference between the two represents the departure from desired/reference conditions.

Planning and Prioritization – The model allows for flexibility in varying the type, extent, and placement of treatment alternatives, which can identify optimal treatment types and locations to meet desired forest structure, fire hazard, and soil loss metrics in different management areas. The same approach can used in alternative development as required by NEPA by simulating ecological impacts of user-defined management alternatives (i.e., treatment scenarios).

Monitoring and evaluation – Spatial implementation monitoring data can be incorporated into the CEAP framework by augmenting fuel models based on local information on treatment effects or mean effect sizes of different treatment types. The model can then be re-run as new treatments occur to evaluate cumulative effects of treatments on landscape-scale structural heterogeneity, fire hazard, and soil loss metrics at the Forest or watershed-level. Cannon (2019) piloted a proof-of-concept model in the Jefferson County Open Space to demonstrate how the CEAP approach can be used to link project-level forest vegetation management outcomes to landscape-scale (HUC-12) conditions, i.e., to assess how individual projects contribute to landscape-scale desired conditions.

Advantages and limitations – The CEAP model framework explicitly models outcomes to structural heterogeneity, fire behavior, and soil erosion, i.e., it addresses all three forest monitoring components of interest in the cooperative agreement. Also, the scenario-based approach is useful for developing alternatives and supports flexible implementation. However, the CEAP model framework does not currently consider treatment constraints/feasibility (e.g., costs, accessibility), or wildfire risk to Highly Valued Resources and Assets (HVRAs – critical water infrastructure, wildland urban interface, etc.). Also, CEAP does not explicitly incorporate the way in which future climate scenarios or climate change risk will impact management strategies and conservation outcomes (see Figure 1).

Quantitative Wildfire Risk Assessment

QWRAs integrate modeling on the likelihood and intensity of wildfire with local knowledge and expertise to determine the susceptibility of Highly Valued Resources and Assets (HVRAs) to wildfire (Scott et al. 2013). The susceptibility analysis relies on expert and local knowledge to identify which HVRAs are of importance, where on the landscape HVRAs exist, and the effects of wildfire on HVRAs (effects analysis) estimated as a response function from total loss to net benefit under different fire scenarios. Relative importance weights of HVRA categories are defined to represent stakeholder values.

A QWRA was developed with the PSICC using the values at risk layer from the Colorado Wildfire Risk Assessment (Technosylva Inc. 2018) to support development of strategic response zones (SRZs) for wildfire response. This existing effort may require refinement using localized input and additional HVRAs to support Forest Plan revision. Also, in a planning context, HVRA development should consider a broader scope of stakeholders than what was considered in the initial effort, and a collaborative process to get buy-in and incorporate the most relevant, inclusive HVRAs to inform future management direction and actions. The initial effort could also be enhanced by leveraging ongoing risk assessment efforts, e.g., the USDA Forest Service regional fire modeling and risk assessment and Colorado All-Lands risk assessment.

Wildfire likelihood and intensity are driven by fuel, weather, topography, and ignition locations. Hazard assessments estimate burn probability (the likelihood that a fire will burn in a given pixel) and fire intensity (or flame length) using a variety of fire modeling systems (Thompson et al. 2016b). There are many models and approaches that may be useful to assess wildfire behavior. We explain one such approach using FlamMap.

First, existing conditions are derived from LANDFIRE. FlamMap can generate estimates of burn probability, fireline intensity, flame length, crown fire activity, and other fire behavior metrics by weather scenario (Figure 2) (Scott et al. 2013). Wildfire hazard components from FlamMap can convey information on the expected watershed area burned by fire intensity level. Next, spatial data on HVRAs, which can include nationally-consistent and local data (e.g., wildland-urban interface, water utilities and infrastructure, critical wildlife habitat, etc.), are acquired and integrated into a Geographic Information System (GIS) to assess exposure to wildfire. Local experts are consulted to estimate response functions for each HVRA, or the direction (positive or negative) and magnitude of wildfire effects on each HVRA, at different fire intensity scenarios. The effects analysis helps estimate the conditional net value change. Conditional net value change is a measure of the anticipated change in HVRAs when exposed to wildfire of different intensities. This metric combines the spatial data of HVRA locations, response functions, and fire intensity scenarios, but does not incorporate burn probability. Expected net value change is then estimated by combining the conditional net value change and burn probability, or the likelihood that fire will occur in a particular location. Composite risk maps are then developed using the expected net value change and relative importance weights for each HVRA category. Which HVRAs are included in the assessment and how their importance is weighted is defined by local stakeholders (Figure 2).

Wildfire likelihood and intensity can also be combined with widely used watershed response functions to estimate relative metrics of risk to watersheds (Thompson et al. 2016b, 2013) or physical process models to quantify metrics such as expected sediment yield and wildfire risk to water supply from post-fire soil erosion (Gannon et al. 2019).
The QWRA framework has been applied across multiple planning contexts and at several scales, for example three forests in Region 5.

Assessment – Scott et al. (2015) developed a region-wide QWRA to encompass the footprint of the Inyo, Sierra, and Sequoia National Forests and support their Forest Plan revision efforts.

Planning and prioritization – The QWRA developed by Scott et al. (2015) was used to designate strategic wildfire management areas. The strategic wildfire management areas included community wildfire protection, general wildfire protection, wildfire restoration, and wildfire maintenance. Desired conditions, goals, standards, and guidelines were established for each management area. These management areas demarcate where risk is high and where risk is low and served as a coarse-scale prioritization tool to identify the right treatment in the right place to meet different desired effects. For example, the community wildfire protection zone documents areas with the highest risk to communities and associated assets. Within this zone, mechanical fuels treatments are prioritized to increase effectiveness of wildfire management. On the other hand, the wildfire restoration zone demarcates areas with low to moderate risk to natural resources. In this zone, managers could prioritize restoration treatments to create more opportunities

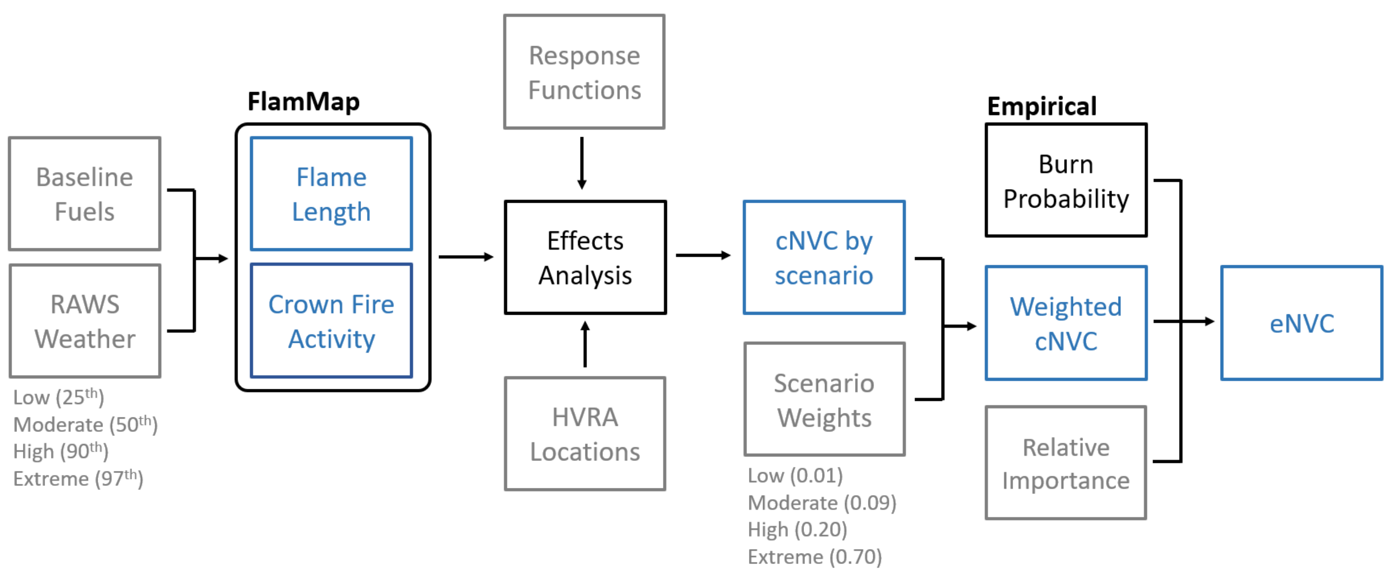

Figure 2: Quantitative Wildfire Risk Assessment. Source: Technosylva 2018.

under a wider range of conditions to use wildfires for resource benefit when they do occur to achieve Forest Plan desired conditions (Sequoia and Sierra National Forests 2019).

Monitoring – There are several opportunities to use the QWRA framework for Forest Plan monitoring:

- The Inyo, Sierra, and Sequoia included the strategic wildfire management areas in their monitoring plan to assess what management actions are contributing to the achievement of desired conditions relating to fire regimes. For example, forest managers track acres of fire by objective within each management zone (Inyo National Forest 2019; Sequoia National Forest 2019; Sierra National Forest 2019).
- Spatial implementation monitoring data can be used to augment baseline fuels data layers at regular intervals to assess change in fire behavior, intensity, and risk at the landscape-scale, i.e., condition net value change.
- Strategic wildfire management areas are not static. The change in categories as a function of repeated fuels reduction treatments, restoration treatments, or changes in vegetation condition due to disturbance could shift a wildfire restoration area to a wildfire maintenance area, for example. Thus, the proportion of forest in each management area category can be monitored through time.

Advantages and limitations–The advantages of the QWRA are that it: has been deployed in several planning contexts; explicitly considers risk to resources and assets of management concern; incorporates the negative and positive impacts of wildfire to resources and assets; and relies on a participatory, iterative process whereby local experts and stakeholders define which resources are important and how important they are relative to others in driving the model results. CFRI developed a Risk Assessment for Priority Investment Decision Support (RAPIDS) tool and graphical user interface (GUI), which supports participatory model development and exploration almost in real-time. Further, managers on the PSI have engaged in QWRA development – data and lessons learned from this approach can be leveraged, refined with updated regional fire behavior data, and expanded through a larger, more inclusive collaborative engagement process suitable for forest planning and cross-boundary collaboration.

Some limitations to the approach are that it does not compare against a natural range of variation; the model is wildfire-centric unlike the CEAP model that incorporates measures of ecological integrity/forest health; and while it is easy to identify desired directional changes, it may be difficult to identify specific desired conditions because wildfire risk has both ecological and social components. When used in isolation, the QWRA does not incorporate treatment feasibility, costs, and budget constraints. Also, QWRA does not explicitly incorporate the ways in which future climate scenarios or climate change risk impact fire behavior metrics and thus wildfire risk to HVRAs (See Figure 2).

Fuel Treatment Prioritization

CFRI developed a fuel treatment prioritization model within its RAPIDS tool to build upon the QWRA. The fuel treatment prioritization model uses a linear optimization modeling approach to prioritize optimal treatment strategies (location, type, extent) under treatment cost, feasibility, and budget constraints to maximize wildfire risk reduction. The model was applied in the Chaffee County, CO case study to support revision of their Community Wildfire Protection Plan (Gannon 2019). We illustrate the participatory process of developing the fuel treatment prioritization model below.

First, local managers and/or stakeholders define which treatment types to consider in the assessment (e.g., mechanical, prescribed fire, mastication) and the spatial decision units relevant to managers (e.g., sub-watersheds). The final composite risk map derived from the QWRA (expected net value change and relative importance weights for each HVRA category) serves as input to the fuel treatment prioritization model (Figure 3a). Empirical estimates of fuel treatment effectiveness are used to simulate wildfire risk reduction under alternative treatment types and scenarios. In other words, the model assesses the difference in fire intensity between untreated (composite risk map) and treated scenarios, and prioritizes the treatment type and area with

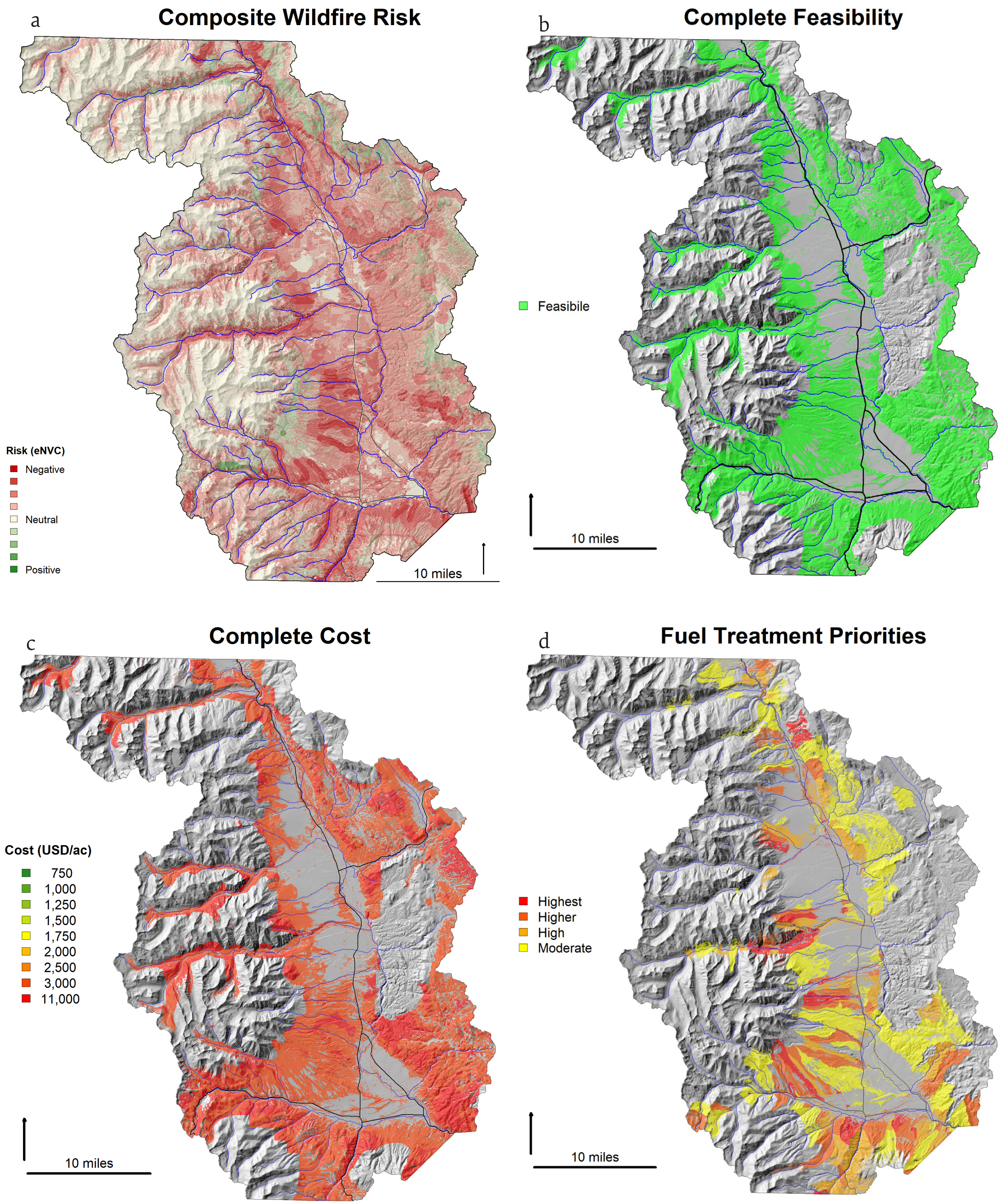

Figure 3: RAPIDs model applied to Chaffee County to inform revision of their Community Wildfire Protection Plan. Maps include: a) composite wildfire risk map from QWRA; b) treatment feasibility; c) treatment cost; and d) fuel treatment priorities to maximize wildfire risk reduction. Source: Gannon 2019.

the highest risk reduction. Treatment constraints are then estimated and mapped as a function of treatment feasibility and treatment cost (Figure 3b, c). For example, in Chaffee County, wilderness areas and roadless areas were not considered feasible for treatment, nor were areas with less than 10% canopy cover. Treatment costs increased as a function of distance from roads and slope, which is a proxy for accessibility and operability. The model is then parameterized, wherein each decision unit includes estimates of feasible area for treatment, mean risk reduction for treatment types, and mean cost for treatment types. Finally, the model is applied to identify spatially-explicit treatment priorities (optimal location, type, and area) that maximize wildfire risk reduction based on a number of budget scenarios (Figure 3d). The same linear program optimization model framework was applied to prioritize treatment to reduce post-fire soil erosion in the Cache La Poudre and Big Thompson watersheds (Gannon et al. 2019).

This tool has utility for Forest planning:

Planning and prioritization – The fuel treatment prioritization model can supplement the QWRA by identifying which watersheds are priority landscapes for treatment (i.e., HUC boundaries or other relevant decision units such as within strategic wildfire management areas), and what is the optimal treatment type, location, and extent to reduce wildfire risk. This can support identification of where to work next and tier vegetation management projects to maximize risk risk reduction over time.

Monitoring – Assessing net value change can be used to quantify outcomes of treatment investments. This uses best available science to apply the right treatment to the right places on the landscape to achieve desired conditions, i.e., reduced risk.

Advantages and limitations– The advantage of this approach is that it: adds treatment feasibility, constraints, and budget scenarios to identify priority treatment locations and type, all of which are necessary considerations for programmatic and project-level planning. It also directly supplements the QWRA, and can be conducted in a collaborative, transparent setting using the RAPIDs GUI interface. The disadvantage is that it is currently focused only on wildfire risk reduction, though CFRI is currently expanding the model to incorporate ecological benefits for ecological restoration/resilience in the absence of wildfire in partnership with the Jefferson County Open Space to support their Land Management Plan revision. Also, RAPIDs does not explicitly incorporate the ways in which future climate scenarios may impact fire behavior, risk, and treatment strategies.

Potential operational delineations (PODs)

PODs integrate advanced fire modeling and spatial analysis with local expertise to demarcate locations on the landscape where fire suppression is most likely to be effective. The boundaries that make up a POD network delineate natural and constructed features on the landscape (e.g., roads, ridgetops, change in fuel type) that are most likely to effectively contain fires.

The process to develop PODs is iterative and participatory and is typically completed over multiple workshops. During these workshops, local experts are provided with maps of suppression difficulty index (a raster layer demarcating areas of high and low suppression difficulty) (Figure 4a), potential control locations (derived from measured and modelled conditions of where fires stopped or kept burning) (Figure 4b), and reference layers (Figure 4c). They then deliberate and hand-draw effective control lines on the maps based on their local knowledge and expertise, which are digitized in a Geographic Information System (GIS) (Figure 4d) (Caggiano 2019). The tool was designed as a pre-season strategic wildfire planning tool, but has been expanded and used during incidents, to prioritize areas for mechanical treatments or bound prescribed burns, and to manage ignitions for resource benefits and restoration objectives (Caggiano 2019). In 2019, PSI developed PODs for the administrative unit in partnership with CFRI, and used the Colorado State Forest Service Wildfire Risk layer to integrate PODs with QWRA.

PODs and associated spatial analytical tools have utility for Forest planning:

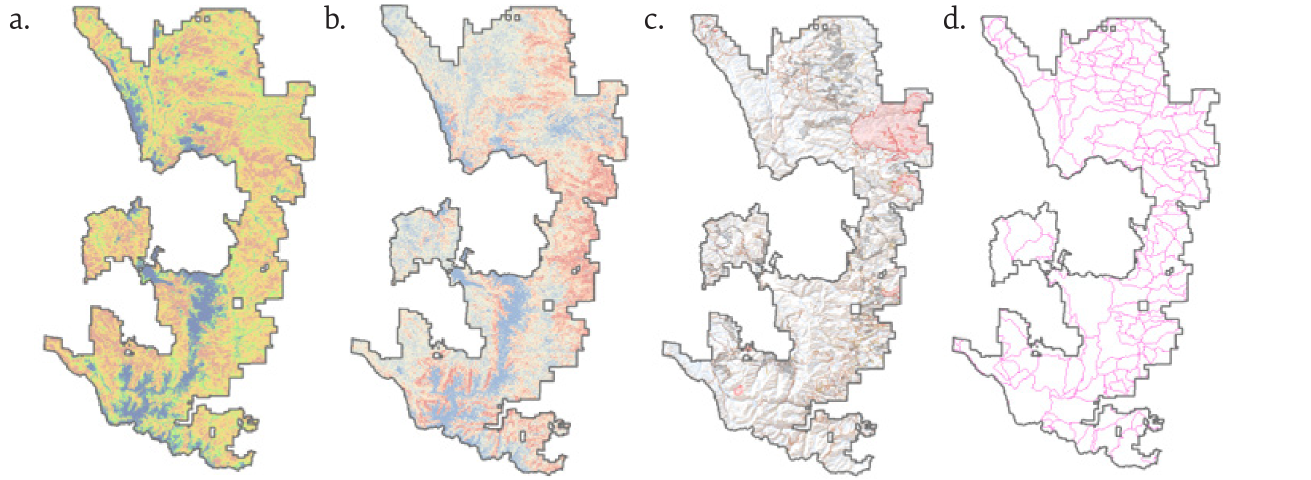

Figure 4: PODs development process. Source: Caggiano 2019. A) Suppression Difficulty Index; B) Potential control lines; C) reference layers; D) Hand-drawn POD boundaries digitized in a geographic information system. Source: Caggiano 2019.

Planning and prioritization – PODs have been used in a few Forest Plan revision processes, notably the Sierra National Forest (Thompson et al. 2016a)and Tonto National Forest (O'Connor and Calkin 2019). In both cases, PODs were used in conjunction with downscaled regional QWRAs to identify strategic response zones (SRZs). SRZs are similar to the strategic wildfire management areas developed from the QWRA in the R5 forests, though boundaries are demarcated based on potential opportunities to contain a wildfire rather than based on land management designations.

On the Tonto National Forest, five strategic response zones were demarcated: 1) protect (high risk, net negative outcome from fire); 2) maintain (low risk, net positive outcome from fire); 3) restore (managed fire under the right conditions); 4) exclude; and 5) high complexity (mix of low-risk fire adapted systems with sensitive infrastructure or other HVRAs) (Figure 5) (O'Connor and Calkin 2019). These zones are used to pre-define potential response options in the event of a fire, though also provide a coarse prioritization tool for different levels and types of treatments. Fuel treatments could be strategically prioritized along control lines or features to "shore up" these lines in the event of high severity fire, for example, and/or prioritized at the boundaries between PODs with different risk levels and response categories (Thompson et al. 2016a). Within "protect" SRZs, primarily mechanical fuel treatments would be used to support more effective fire suppression and prescribed fire would be limited. Alternatively, in the "high complexity" SRZs, strategically placed fuel treatments could be used to develop new control locations, thus separating areas and resources that have wildfire benefit under the right conditions from those that are negatively impacted by fire (O'Connor and Calkin 2019).

Further, the Sierra and Sequoia National Forests used the PODs organizational framework for alternatives development in their joint Environmental Impact Statement (Sequoia and Sierra National Forests

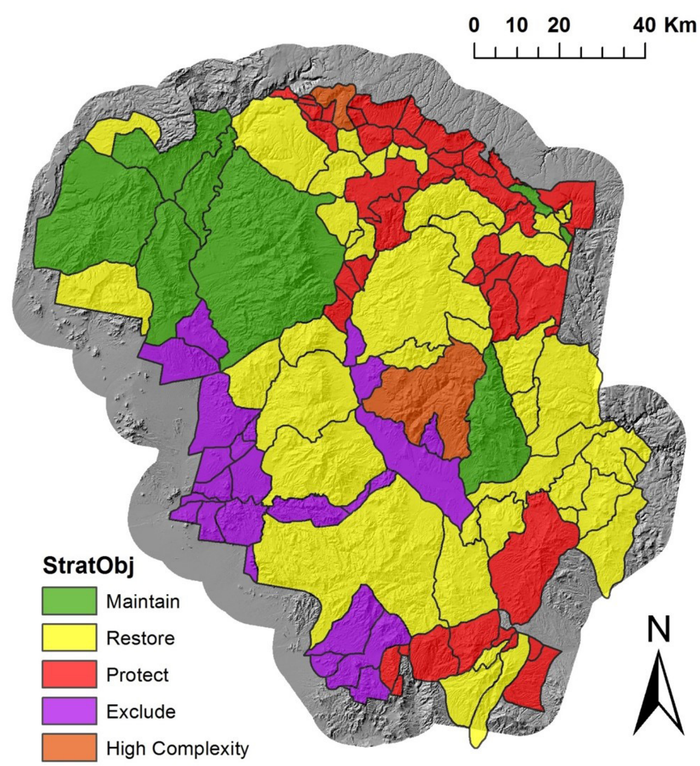

Figure 5: PODs on the Tonto National Forest. Source: Caggiano 2019. Source: Christopher D. O'Connor.

2019). Planners identified focus landscapes using PODs that were near community wildfire protection zones, contained mature forest or fisher linkage areas, and overlapped with areas of moderate to high fire risk. The purpose of the focal landscapes was to increase the pace and scale of restoration in these landscapes such that enough of the landscape is treated to alter wildfire behavior at scale and move the forest towards desired conditions. Within the focal landscape, the alternative prioritized fuel break treatments along PODs boundaries and landscape-scale prescribed burning using PODs boundaries as anchor points, among others.

Monitoring and evaluation – Similar to the Strategic Wildfire Management Areas, SRZs are not static – change in vegetation condition due to treatment or managed wildfire under the right conditions could move a "restore" SRZ to a "maintain" SRZ. Tracking both the number and acres of wildfire managed for resource benefit and the proportion of the Forest in each SRZ can be monitored through time, as was the case in the Tonto National Forest Draft Land Management Plan (Tonto National Forest 2019).

Advantages and Limitations – PODs help in spatial wildfire planning to identify locations where fire may be successfully contained. The added benefit of incorporating PODs with QWRA outputs summarized at the POD-scale provides opportunities to pre-define wildfire response and prioritize treatment strategies for land management objectives. CFRI and PSICC engaged in this process in 2019, which provides an opportunity to leverage and refine this work, as appropriate, to fit planning needs. In this vein, the Rocky Mountain Research Station, CFRI, and other partners are prototyping a POD Atlas on the PSICC and other forests. The PODs Atlas is a decision support tool and workflow that summarizes forest conditions, QWRA outputs, and other data pertinent for fire management, response, and other land management objectives within PODs (Thompson et al. 2020). Data is available as a summary geodatabase and map-books. On the PSICC, data layers in the database for reference include nationally-consistent data and locally-relevant data (e.g., count and location of species of conservation concern, roadless areas, structures, erosion hazard). The data contained in the geodatabase may inform other program area planning efforts and additional data could be supported, thus offering a useful "clearinghouse" of spatial data to inform planning.

Still, PODs as a planning tool for fire and land management objectives requires integration with underlaying QWRA for fire behavior metrics or to develop Strategic Response Zones that determine desired or undesired fire effects. Further, some resource specialists may be hesitant to incorporate a PODs organizational framework in supporting non-fire land and resource management objectives.

Conclusion

Here, we described the ways in which four spatial analytical decision support tools have been, or could be, used to support Forest Plan revision. Each of these tools can support Plan assessment, planning/prioritization, and monitoring. Developing spatially-explicit management plans, priority investments, and monitoring results can help USFS managers better illustrate changes and outcomes when compared to more abstract, nonspatial output reporting, such as acres treated. When metrics are not situated in a geographic context, it may be difficult for appropriators, overseers, stakeholders, and the general public to determine whether investments are worthwhile.

It is important to note that each of these tools have strengths and limitations to consider, and each differ in how they address the Forest plan monitoring components of interest in the PSICC/CFRI cooperative agreement (Table 1). The Forest plan monitoring components of interest included: i) Restoring and sustaining ecological integrity of forest vegetation structure and composition; ii) Reducing unwanted wildfire and promoting desired fire behavior and effects; and iii) Enhancing the resilience and sustainability of source-water resources through reducing soil loss from high-severity wildfire (See Table 1). The CEAP coupled modeling framework addresses all three components of interest, with the caveat that while the model can evaluate treatment effects on wildfire behavior, it does not assess treatment effects to HVRAs. The QWRA and RAPIDs assessment tools are currently wildfire-centric and they have been deployed to address components ii and iii. These tools do not evaluate ecological integrity of forest vegetation structure and composition (i). Used in isolation, PODs do not address any of the Forest plan monitoring components of interest. However, we reviewed applications of incorporating QWRAs into PODs, which can be used to demarcate strategic response zones and prioritize treatment locations and types that reduce unwanted and promote desired fire behavior and effects (ii). PODs are spatial containers within which spatial data can be populated and summarized. Thus, one could use PODs as an organizational framework, or decision unit, and integrate the other spatial tools described herein to address other Forest plan monitoring components of interest as applicable.

Thus, the appropriate tool or tools for Plan assessment, planning, and/or monitoring will ultimately on local needs and priorities. The decision support tools described herein are not mutually exclusive. There is a great deal of overlap between them, and there are opportunities to integrate tools to support Forest planning as appropriate.

CFRI is asked more and more from our local, regional, and national partners to assess approaches for linking treatment outcomes to landscape-scale conditions. Each of these tools use LANDFIRE for baseline vegetation and fuels layers, which provides an opportunity to assess project outcomes on landscape-scale conditions by augmenting fuels layers iteratively as new spatial implementation monitoring data becomes available. Monitoring data from the Colorado Front Range CFLRP and Forest to Faucets program on, and adjacent to the PSI, as well as common stand exam with pre- and post-treatment conditions may be used to localize model outputs (See Section II below).

Still, the extent to which monitoring data can be integrated into these modeling approaches depend on the type, resolution, and quality of monitoring data. A constraint in using implementation monitoring data is that conditions before and after treatment or the intensity of treatment are often not reported, or disproportionately reported across the landscape. It will be important to continue discussions between CFRI, PSICC, and other partners on what monitoring data may be available and appropriate to help ground-truth these modeling tools and make them more relevant to local conditions.

Another constraint to linking treatment outcomes to landscape-scale conditions is driven by institutional and organizational factors within and between administrative units (Wurtzebach et al. 2019). At the local level, administrative units are given some discretion to determine what to monitor and how. This results in a great deal of variability in the monitoring programs and the standards applied to them even across districts of an administrative unit. Different interpretations of what to collect, how to input, etc. challenge data quality control. Further, monitoring focused on short-term goals and efforts limits the ability to assess long-term trends, especially if/when these programs are discontinued following personnel changes.

At the Regional level, there is a need to invest in monitoring specialists, coordinators, and database management specialists to standardize forest monitoring protocols, standards, and data management strategies. In Region 1, for example, the Region has: a) strategically invested in hiring monitoring and analytical specialists to support Forests with monitoring and evaluation; b) worked with FIA program managers to develop intensification and after-disturbance plots and align regional monitoring protocols with FIA assessments to inform multi-scale assessments; and c) developed and curated a regional geospatial database where all the information is housed and available (Hoover et al. 2020). Similar investments are needed in the Rocky Mountain Region in order to better link treatment outcomes to landscape-scale conditions and to support Forest- and broader-scale monitoring required under the Planning Rule (Wurtzebach et al. 2019).

Section II: CFRI and USDA Forest Service Stand and Landscape-scale Monitoring Resources for Forest and Broader-scale monitoring and evaluation

Introduction

This section of the report describes the type of monitoring data that is collected and managed by CFRI and the USDA Forest Service both inside and adjacent to the PSICC, and offers a set of other potential data sources that may be useful for Forest and Broader scale monitoring and evaluation. The section proceeds as follows. First, we outline a framework for monitoring at stand and landscape scales. Second, we provide more detail on the monitoring projects CFRI currently manages inside and adjacent to PSICC boundaries. We include a brief description of the monitoring efforts, what data is collected, where it is collected, and what questions can be addressed with this data. Third, we highlight the FIA program and new open-source tools to query, visualize, and analyze FIA data at multiple scales. FIA data is increasingly used to support Forest Plan monitoring and evaluation, as well as the broader-scale monitoring requirements of the 2012 Planning Rule. Fourth, we include a small list of additional relevant datasets that may be used for planning, monitoring, and evaluation at multiple scales.

A general framework for monitoring at stand and landscape-scales

Effective monitoring relies on clearly stated monitoring objectives and the identification of the metrics that can be used to assess progress in achieving goals and desired conditions at the stand- and landscape-scale. RMRS General Technical Report-373 Principles and Practices for the Restoration of Ponderosa Pine and Dry Mixed-Conifer Forests of the Colorado Front Range (GTR-373) provides an outline of key attributes of landscape and stand structure that can be efficiently measured by common monitoring metrics to provide information about forest structure, composition, and function at the stand-scale and landscape-scale (Addington et al. 2018). Although these metrics, and their methods of measurement are continually evolving, they can provide a useful reference for planners and managers on the PISCC.

In consultation with John Dow, PSICC Forest Planner, and Ed Biery, Vegetation mapper/GIS specialist, we used the GTR-373 framework to create a series of tables that compare existing monitoring efforts managed by CFRI and the USDA Forest Service within and adjacent to the PISCC *(Appendix A)*. The tables aggregate metrics collected from CFRI's monitoring efforts and identifies similar metrics collected by the USDA Forest Service FIA and CSE monitoring programs. The purpose of this was to identify where common stand-scale monitoring data may exist across projects. It may be possible, then, to assemble data from spatially disaggregated efforts to address more regionalized questions. Alternatively, this effort identifies gaps in the types of data collected across monitoring projects, and thus the challenges with aggregating existing monitoring projects that were not designed to interface. In this vein, the PSICC forest planner was also interested in this effort to inform future monitoring efforts that complement ongoing efforts, and which may be used for multi-level assessments.

CFRI Monitoring Data

Here, we provide more detail on the projects that CFRI monitors within the PSICC and adjacent to the PSICC (Figure 6). We include the purpose of the study and links to relevant monitoring reports and information. The monitoring projects that CFRI manages assess the effects of treatments on forest structure, composition, and heterogeneity, surface fuel conditions and potential fire behavior, and understory plants. We refer the reader to Appendix A, which compares stand-scale metrics (Table A1) and description of the metrics (Table A2) between CFRI- and USFS-managed projects.

Forests2Faucets – USFS & Upper South Platte Partnership

CFRI manages pre- and post-treatment monitoring plots for the Forests2Faucets (F2F) program in the north and northeast portions of the Pike National Forest, the Arapaho-Roosevelt National Forest, and in partnerships with the Upper South Platte Partnership (USPP) on private and non-federal lands near the boundary of the PISCC (Figure 7). The F2F and USPP monitoring programs include effectiveness monitoring of forest structure and spatial arrangement, fuels, and understory plants using a variety of plot-based assessments, fire behavior modeling, and remote sensing. Although treatment types and intensities vary by project, monitoring protocols and reporting for each were consistently applied. Pre-treatment monitoring

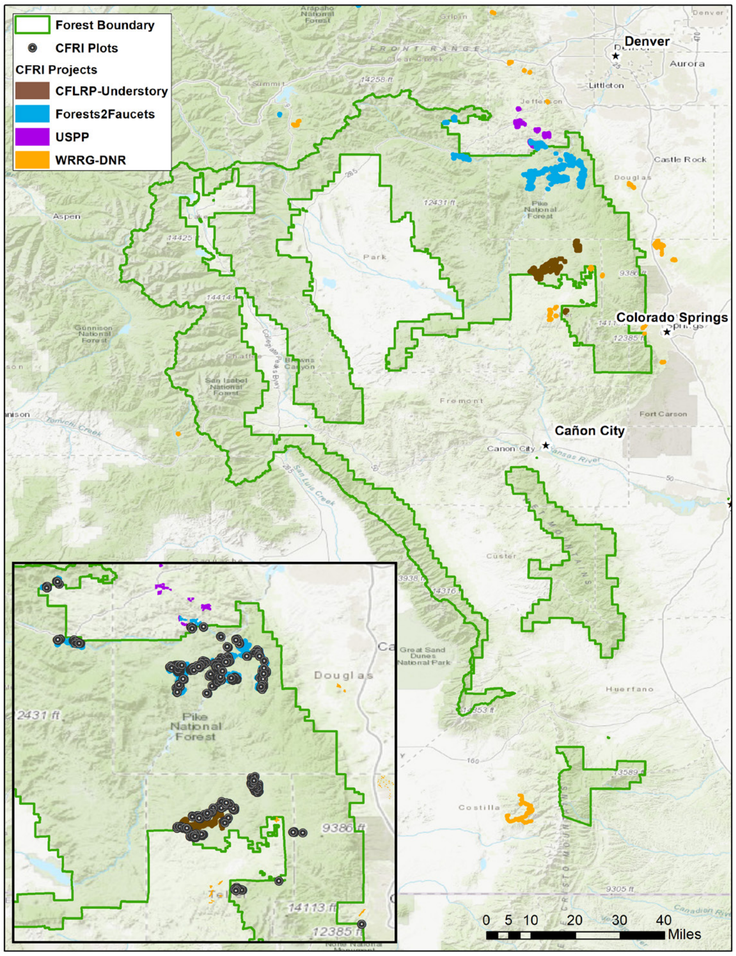

Figure 6. Location overview of the two monitoring projects managed by CFRI within the PISCC forest boundary and two projects managed on public and private lands near to the PISCC. Inset shows a close-up of all plots within the PISCC boundary.

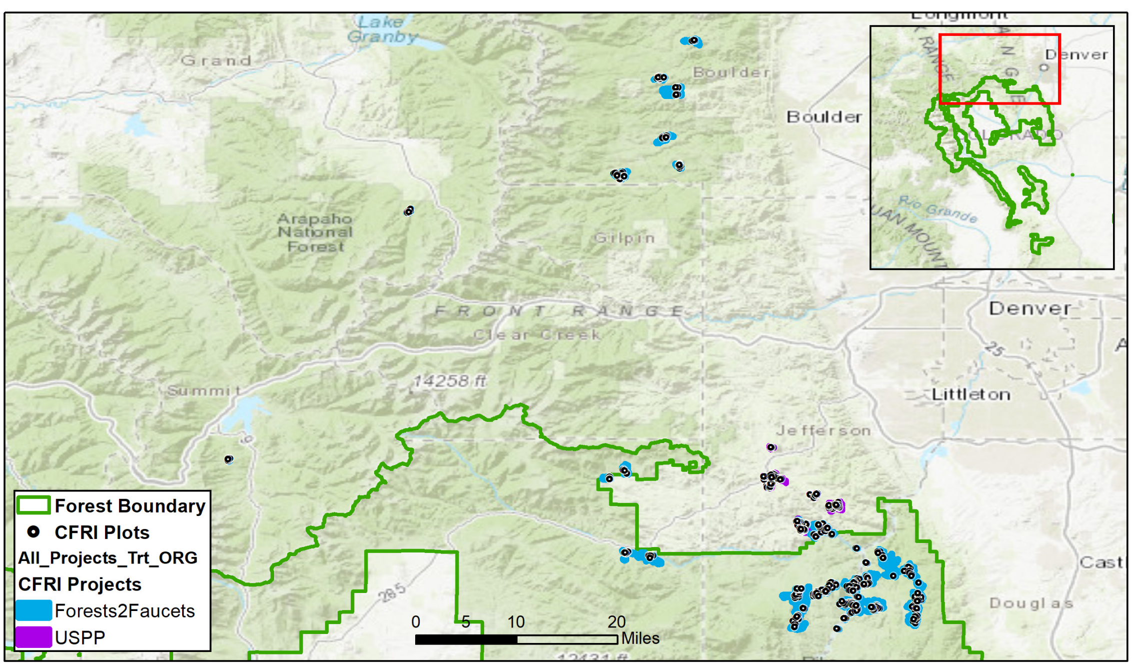

Figure 7. Overview map of treatment boundaries and plots monitored by CFRI within the PISCC for the Forests2Faucets and USPP monitoring program.

was followed up by 1 year and 5 years post-treatment monitoring in order to determine treatment effectiveness and longevity. The F2F project includes 586 plots in 78 project locations across both forests with 276 monitoring plots in 28 treatment project locations on the PISCC. CFRI assessed treatment effectiveness and longevity of wildfire risk reduction activities completed between FY2010-2015 and continued to intensively monitor approximately 20% of the treatments from FY2016-2020. Monitoring of a portion of the projects is expected to continue in the 2021 field season and beyond pending funding. For a more detailed example of a draft monitoring report for the F2F monitoring program, see Appendix B. The final report is forthcoming in early 2021.

Landscape Scale Spatial Heterogeneity Remote Sensing Analysis

Restoration goals for dry forests include increasing spatial heterogeneity and the number and extent of gaps, which in turn can enhance resilience to wildfire and drought, promote diversity in understory vegetation, and enhance wildlife habitat. To address this, CFRI measures changes in canopy cover and gap structure using supervised classification of pre- and post-treatment imagery (Cannon et al. 2018) (Figure 8). Briefly the methods include:

- Acquire leaf-on, snow-free pre- and post-treatment satellite imagery for treated sites from WorldView, GeoEye, or Quickbird satellite with 3-m pixel resolution and derive the normalized difference vegetation index (NDVI) to aid in classification.
- Stratify approximately 100 training areas in each image and use supervised random forest classification to classify each image into canopy and openings.
- Delineate large gaps, which are defined as continuous regions with <5% canopy cover over an area of 0.11 ac (40 ft radius). Although the definition of gaps can vary depending on the ecological process of interest, this scale was chosen because resource abundance and growth of regenerating seedlings are predictable in neighborhoods of approximately 40 feet radius in size (Boyden and Binkley 2016).
- From the resulting canopy, opening, and large gap data, estimate pre- and post-treatment averages and variability of canopy cover and cover of large gaps at a 3- m scale. Using individually identified gaps, calculate gap size distributions and assess gap size variability using the coefficient of variation (standard deviation/mean) of gap size.

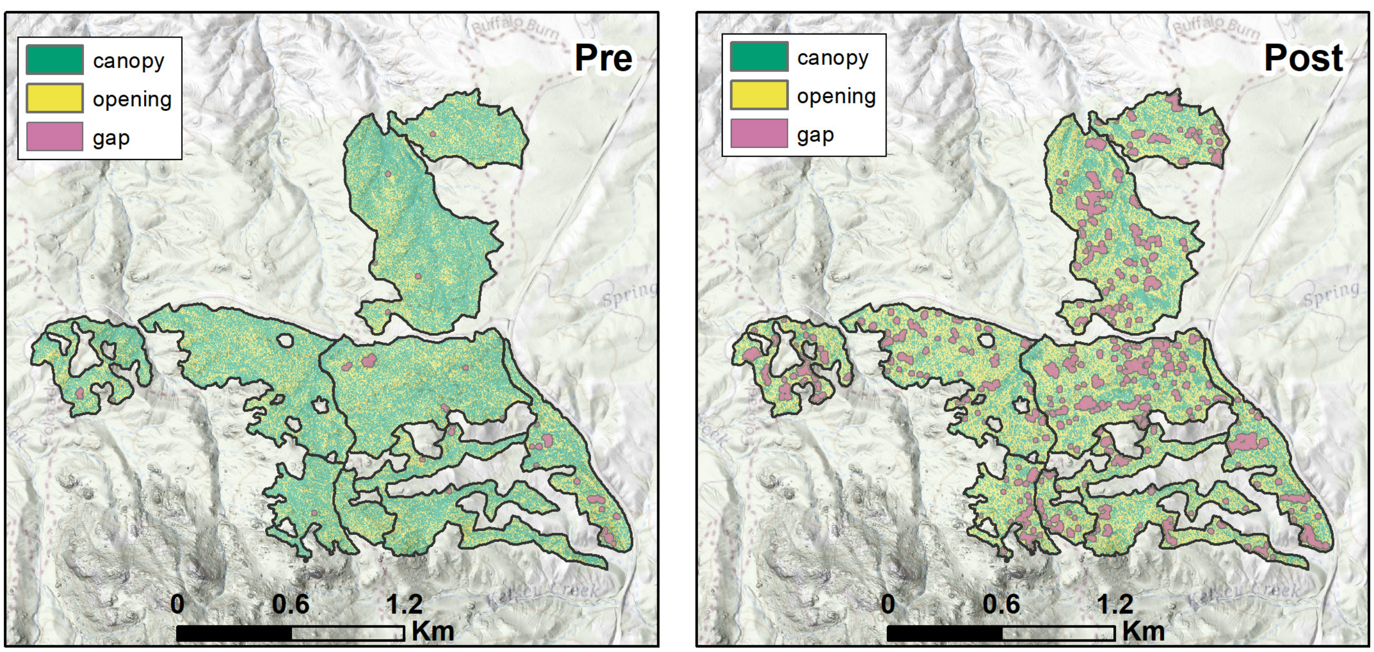

Figure 8. Example of output from the landscape scale spatial heterogeneity analysis. The above is one example from the F2F project's Little Morrison treatment site; the left panel depicts pre-treatment conditions and the right panel depicts post-treatment conditions.

Currently, this analysis has been completed on all F2F project locations, including USPP project locations, except on two treatment areas where post-treatment imagery was not yet available. CFRI has used this analysis at the project level only. The supervised classification step is both time and labor intensive. Each downloaded image is equal to approximately one square mile and must be classified individually. Larger projects or landscape-scale efforts would require stitching multiple images together.

Colorado Front Range Collaborative Forest Landscape Restoration Project – USFS

In 2010, the Pike and San Isabel National Forests along with the Arapaho and Roosevelt National Forests were awarded funding under the USDA Forest Service Collaborative Forest Landscape Restoration Program (CFLRP, https://www.fs.fed.us/restoration/CFLRP/index.shtml). The CFLRP provides 10 years of funding for collaborative forest restoration implementation and monitoring. The Colorado Front Range Landscape Restoration Initiative was funded to reduce the risk of ecologically uncharacteristic and socially undesirable wildfires on 32,000 acres of lower montane, ponderosa pine (Pinus ponderosa) dominated National Forest lands. The CFLRP project specifically aimed to:

1) Establish a complex mosaic of forest density, size and age (at stand scales)
2) Establish a more favorable species composition favoring lower montane over other conifers.
3) Establish a more characteristic fire regime.
4) Increase coverage of native understory plant communities.
5) Increase the occurrence of wildlife species that would be expected in a restored lower montane forest.
6) Establish a complex mosaic of forest density, size and age (at landscape scale)

The CFLRP monitoring program includes 90 monitoring plots in 4 treatment project locations in the PSICC (Figure 9). CFRI monitored the pre- and post-treatment monitoring plots for the CFRLP program in the northeast portions of the Pike National Forest from 2010 to 2020 (Figure 9). Additional monitoring questions and a monitoring plan were developed in 2014 under a grant from the Southern Rockies Landscape Conservation Cooperative (SRLCC) to include a strong emphasis on evaluating understory plant impacts, such as treatment effects on total native plant cover and diversity. Briggs et al. (2017) found that CFLRP restoration treatments have been successfully shifting forest structure

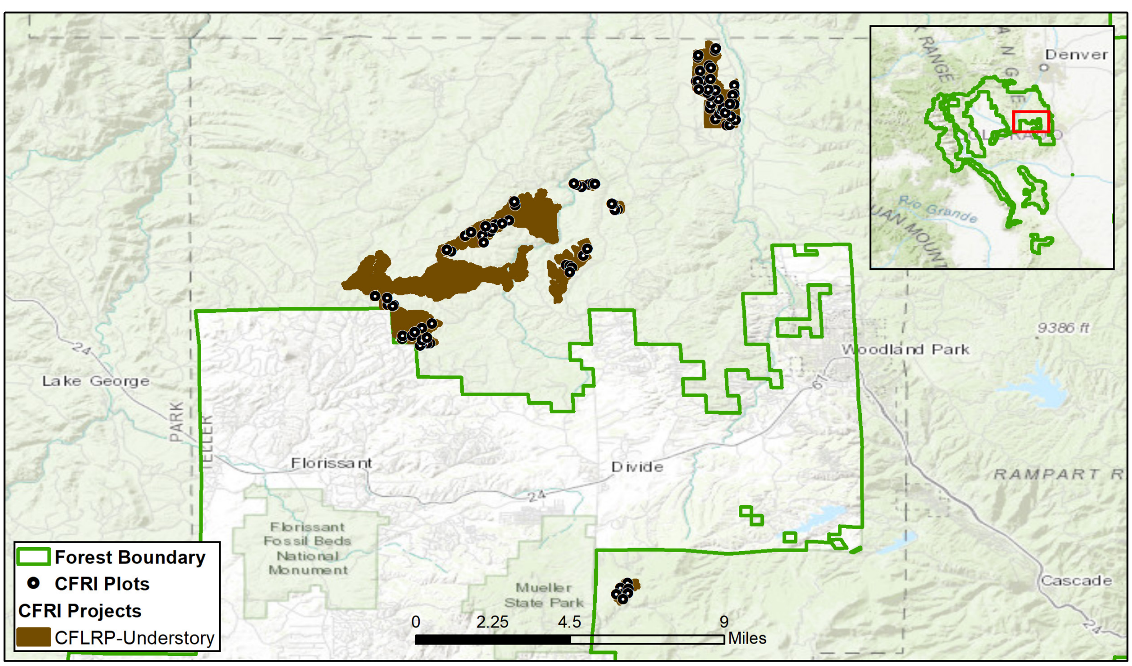

Figure 9. Treatment boundaries and plots monitored by CFRI within the PISCC for the CFLRP Understory monitoring program.

toward desired conditions, including decreasing forest densities, increasing forest heterogeneity, and increasing herb cover without significant impacts on wildlife use.

Wildfire Risk Reduction Grant - DNR – Coalition for the Upper South Platte

From 2013-2017, the Colorado General Assembly funded the Wildfire Risk Reduction Grant (WRRG) program to enhance the capacity of local government, community-based organizations, and private property owners to reduce flammable fuels on non-federal lands in and around their communities in order to mitigate the risk of losses from wildfire. WRRG monitoring assessed the effectiveness of these hazardous fuel reduction treatments on forest structure and expected fire behavior.

CFRI managed the WRRG monitoring program on private and other non-federal lands, including some projects which fall within or near the PSICC boundary (Figure 10). The WRGG monitoring program was comprised of field-based measurements of fuel conditions before and after treatment activities, and computer fire simulation modeling to estimate changes in fire hazard metrics. The monitoring effort included 236 monitoring plots in 25 treatment project locations across the state of Colorado. The project was monitored by CFRI from FY2013-2017. No future monitoring at these sites is planned by CFRI at this time. To see the final monitoring report, see Morici et al. (2019).

USDA Forest Service Forest Inventory and Analysis (FIA) Program

Data from the USFS Forest Inventory and Analysis (FIA) program has the potential to complement CFRI-collected data and support Forest planning. Given its robust and spatially balanced "all lands" sampling grid, extensive plot-level data, timely remeasurement cycles, ability to quantify uncertainty, and dedicated funding from Congress, the FIA program represents the agency's best available scientific information for many forest-planning topics, and it is an important resource for meeting the adaptive management intent of the planning rule (Wurtzebach et al. 2020).

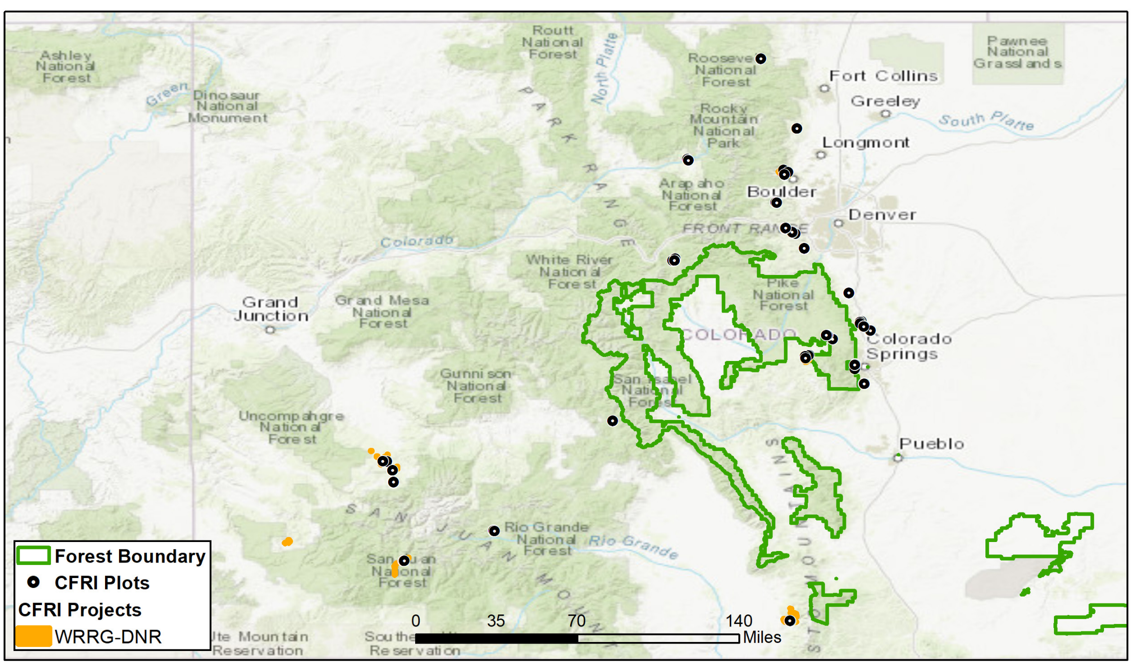

Figure 10. Treatment boundaries and plots monitored by CFRI across Colorado for the WRRG monitoring program. The WRRG targets private and non-federal lands.

FIA forest-plot data are remeasured on a 10-year cycle in the western United States (Figure 11) and consist of three phases:

- Phase 1 consists of selecting sites via remote sensing and assigning forest/non-forest classification.
- Phase 2 consists of one field sample site for every 6,000 acres. Field crews collect data on forest type, site attributes, tree species, tree size, and overall tree condition on accessible forest land.
- Phase 3 samples a subset of Phase 2 plots that are measured for a broader suite of forest health attributes, including tree crown conditions, lichen community composition, understory vegetation, down woody debris, and soil attributes. All of the plots in the PSICC are included in the phase 3 subset. For a full list of metrics assessed and FIA protocols, see the Forest Services' FIA Library at https://www.fia.fs.fed.us/library/field-guides-methods-proc/index.php

rFIA (https://rfia.netlify.com/) is an R package aimed at increasing the accessibility and use of the FIA database. The package allows the user to easily query and analyze FIA Data for a specified forest or region. Data can be analyzed at fine spatial scales to Plan-level scales and be summarized by user-defined polygons and timeframes. We provide one example below using rFIA to estimate annual tree per acre (TPA) in the PSICC through time (Figure 12). Because rFIA accesses the Forest Inventory and Analysis Database, the list of forest variables available for analysis is extensive. See database documentation for a complete list of forest variables here: https://www.fia.fs.fed.us/library/database-documentation/index.php. In Figure 13, we overlaid FIA and CFRI monitoring data with HUC 12 watersheds within the PSICC to illustrate the potential for watershed-scale analysis within the forest.

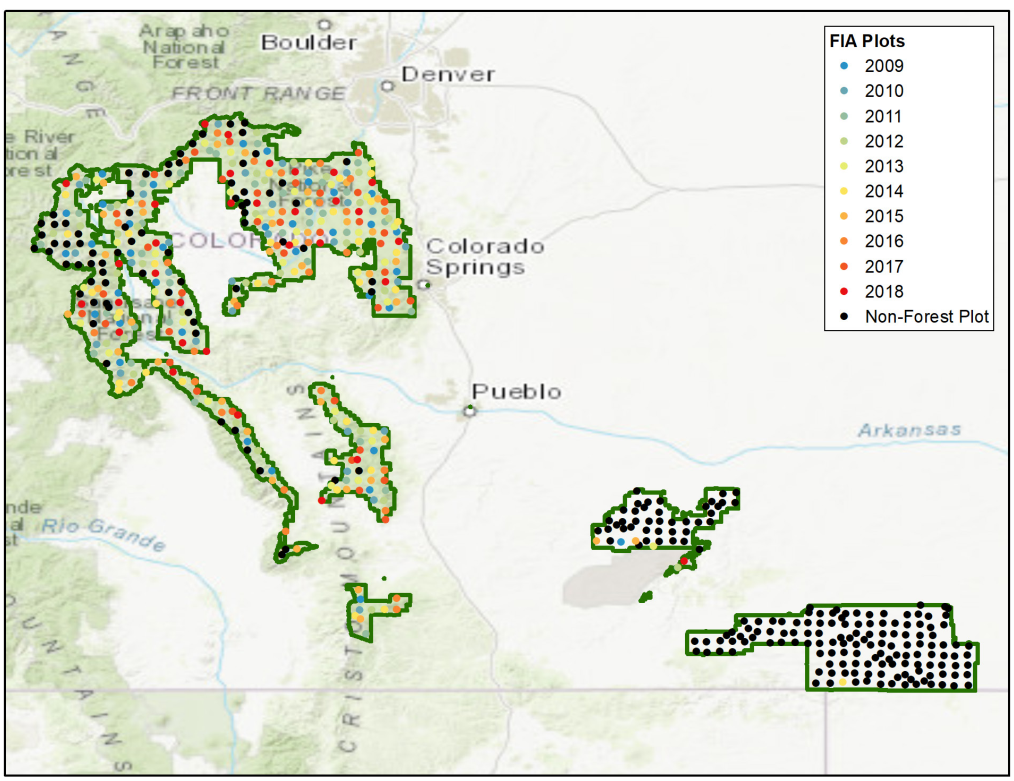

Figure 11. Estimated plot locations across the PISCC. Map shows the most recent inventory analysis year for each plot.*
**All FIA plot coordinates are depicted within 0.5 miles to 1.0 mile from actual location.*

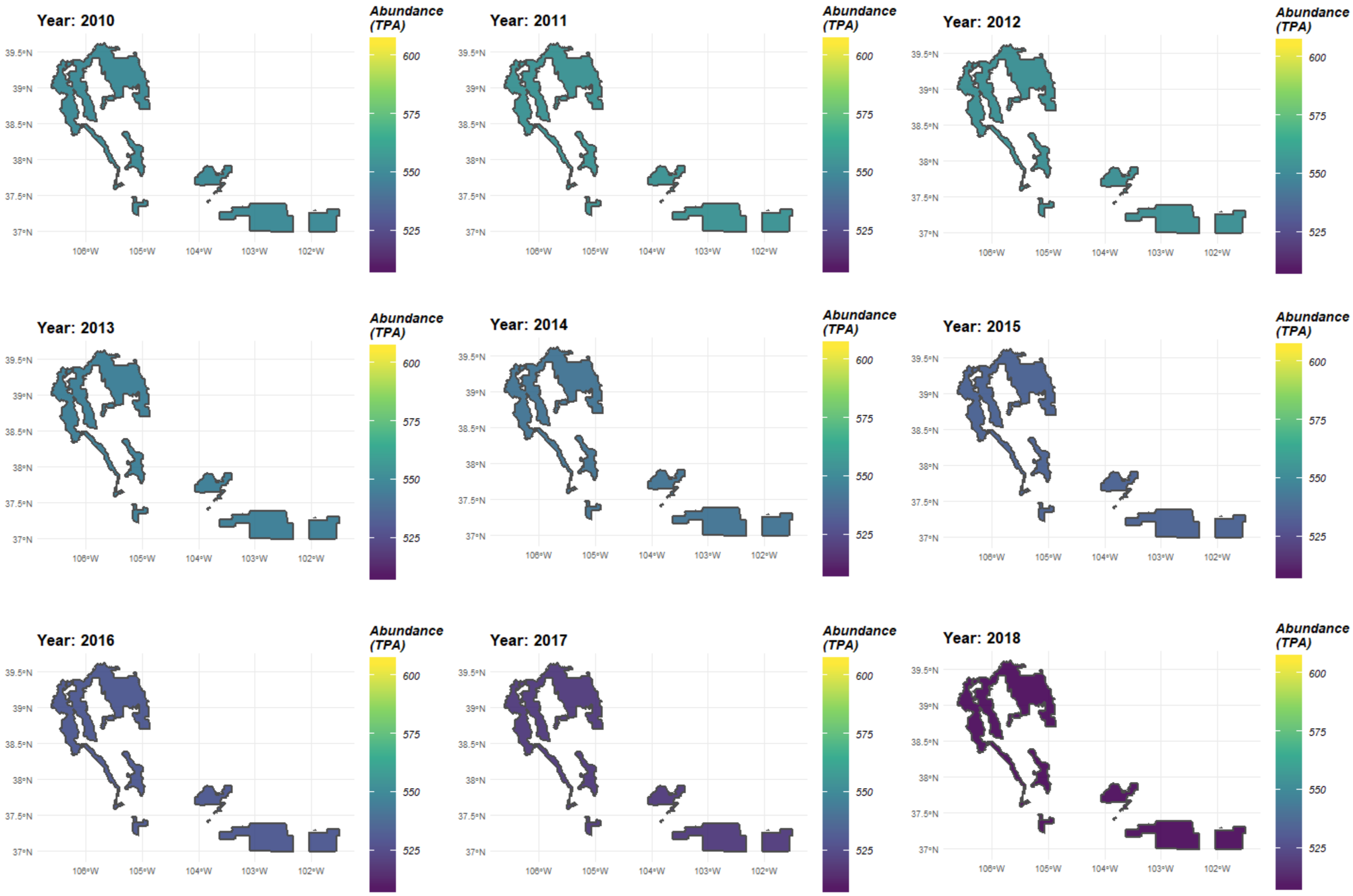

Figure 12. Example of data obtained from rFIA package in R. Annual tree per acre (TPA) estimates from FIA data for 2010 - 2018. Estimates can be produced for regions defined within the FIA Database, at the plot level, or within user-defined spatial scales. Assessments are also possible across different time scales.

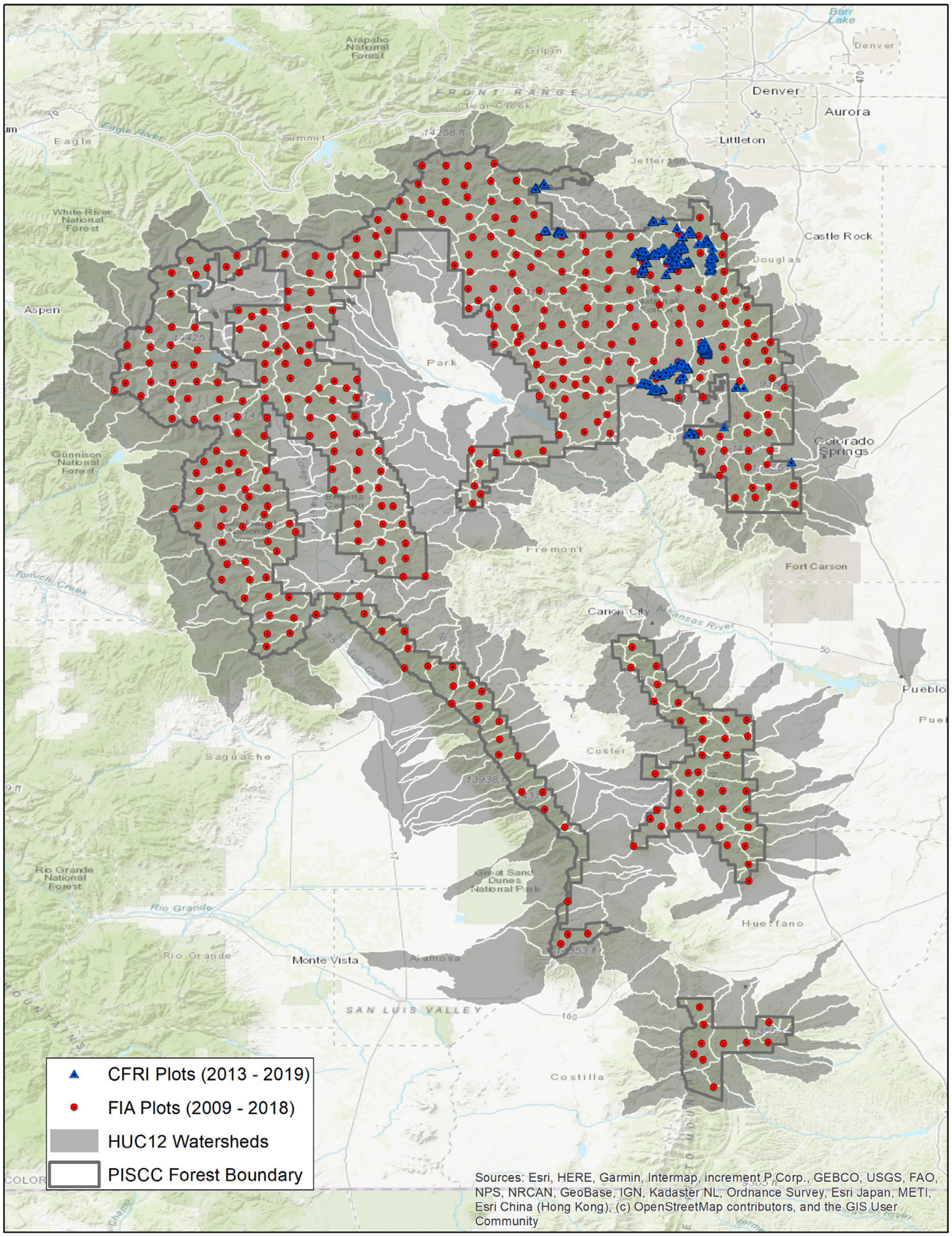

Figure 13. Monitoring plots overlaid on HUC12 watersheds within the PISCC shows the potential for watershed-scale analysis within the forest.

Additional datasets to support Forest plan monitoring and evaluation

Table 2 provides a brief list of other potential datasets that may support Forest plan monitoring and evaluation.

Dataset	About/Description	Weblink
Center for Disease Control Social Vulnerability Index (SVI)	The Center for Disease Control Social Vulnerability Index uses U.S. Census Data to determine the social vulnerability of communities at the census tract level based on 15 social factors and 4 themes: socioeconomic status; household composition; race, ethnicity, and language; and housing/ transportation. This database can be used to identify marginalized and environmental justice communities.	https://www.atsdr.cdc.gov/placeandhealth/svi/index.html
Insect and Disease Detection Survey database	Detection surveys are the primary method of collecting data on the health of forests affected by pest and pathogen disturbances. These are used to produce the Forest Insect and Disease Conditions in the United States reports and the National Forest Health Conditions and Highlights Interactive Story Maps. Data is available to download by region and for individual years or throughout the period of record.	https://www.fs.fed.us/foresthealth/applied-sciences/mapping-reporting/detection-surveys.shtml
National Insect and Disease Risk and Hazard Mapping	The 2012 National Insect and Disease Risk Map (NIDRM) is a nationwide assessment of the hazard of three mortality due to insects and disease. NIDRM is a strategic planning tool, the purpose of which is to support administrative activities and work planning. The data is available across the U.S. at a 240-meter resolution. The data can be summarized at 6th level Hydrological Unit Code (HUC) sub-watersheds, and allows the user to generate both composite hazard assessments and assessments by specific insects and diseases.	https://www.fs.fed.us/foresthealth/applied-sciences/mapping-reporting/national-risk-maps.shtml
Monitoring Trends in burn severity (MTBS)	Monitoring Trends in Burn Severity (MTBS) maps the burn severity and extent of large fires across all lands of the United States from 1984 to present. This includes all fires 1000 acres or greater in the western United States and 500 acres or greater in the eastern Unites States.	https://www.mtbs.gov/
Integrated monitoring in bird conservation regions/Bird Conservancy of the Rockies	This database includes current data and results collected by the Bird Conservancy of the Rockies and collaborators. Data on focal and sensitive species, as well as trend estimates of bird populations can be queried at multiple scales. Data ib sensitive species for each National Forest have been estimated and can be queried. Raw data and specific data requests not available on the portal can be requested and supported through data sharing agreements.	http://rmbo.org/v3/avian/Home.aspx

Dataset	About/Description	Weblink
The Climate Toolbox	The Climate Toolbox hosts a collection of web tools for visualizing past and projected climate and hydrology of the conterminous United States. The website includes several applications for addressing questions related to agriculture, climate, fire conditions, and water. Users can query and download tabular, graphical, and spatial data for use in planning and analysis. In addition to a number of tools and applications, this website provides extensive guidance on how to use climate data to support management actions and build resilience to climate change.	https://climatetoolbox.org/
CPW All Species Monitoring Data	Colorado Parks and Wildlife (CPW) GIS Unit created the CPW All Species Activity Mapping Data layer package in 2020 to provide open access to data on wildlife distributions.	https://www.arcgis.com/home/item.html?id=190573c5aba643a0bc058e6f7f0510b7
Wildfire risk to communities	Wildfire Risk to Communities database was developed to help communities to understand, explore, and reduce wildfire risk. Data is available for download data at the community, county, and state levels. Data for download include: risk to homes; burn probability or wildfire likelihood; exposure types (direct or indirect); wildfire consequence; conditional flame length; flame length exceedance probabilities; and wildfire hazard potential. Other housing unit data will be available for download soon.	https://wildfirerisk.org/
Colorado Forest Atlas	The Colorado Forest Atlas includes three public applications (forest action plan 2020; wildfire risk viewer; and risk reduction planner), which can be used for project development, forest management planning, and wildfire risk and forest condition assessment. Data is not available for direct download, but county-level map books can be downloaded to explore Forest Action Plan theme maps and goals.	https://coloradoforestatlas.org/
EPA Critical Loads Mapper	The Critical Loads Mapper tool provides information on effects from atmospheric nitrogen (N) and sulfur (S) deposition.	https://www.epa.gov/air-research/critical-loads-mapper-tool
Landscape Dynamics Assessment Tool (LanDAT)	LanDAT is a vegetation monitoring tool for assessing whether changes to landscapes are meeting desired conditions and for assessing landscape resilience.	https://landat.org/

Dataset	About/Description	Weblink
Rangeland Analysis Platform	The Rangeland Analysis Platform (RAP) summarizes trends in rangeland resources at multiple scales (pasture, landscape, regional). The RAP pairs ground-based measurements with satellite imagery to estimate percent vegetation cover of different cover types.	https://rangelands.app/
National Forest Socioeconomic Indicators Tool	The National Forest Socioeconomic Indicators was developed to support Forest planning and Forest NEPA project documentation at multiple scales. It supports monitoring contributions and impacts of management actions to surrounding communities.	https://headwaterseconomics.org/tools/forest-indicators/

Conclusions and next steps

In this report, we:

1) Identified the ways in which four spatial analytical decision support tools can inform assessment, planning, and monitoring under the 2012 Planning Rule, with a specific focus tools to assess and monitor forest structure and composition, wildfire risk, and post-fire soil erosion; and

2) Described the monitoring projects that CFRI manages inside and adjacent to the PSICC boundaries. We compare these to USDA Forest Service monitoring efforts (Forest Inventory and Analysis (FIA), common stand exam (CSE)) to assess comparability across projects and inform future monitoring efforts

Our hope is that this report sufficiently addressed the objectives of our cooperative agreement.
In the course of multiple, iteratives discussions with the PSICC planner and staff, we have started working towards a few next steps that may inform future programs of work and cooperative agreements in supporting Forest Plan monitoring and evaluation.

First, we worked with the PSICC forest planner to co-develop and submit a proposal to the Regional Office for funding to develop a Forest-wide quantitative wildfire risk assessment and fuel treatment prioritization model to support Forest Plan revision (currently scheduled for 2024). The proposal would have tiered off a parallel agreement with the Arapahoe and Roosevelt National Forests and CFRI, the overall goal of which was to develop a Front Range-wide all-lands standardized assessment to support Forest- and landscape-level planning and cross-boundary forest restoration. Although the proposal was not funded, we will continue to search for additional funds or ways to leverage funds and support this project. The South Platte Ranger District is initiating a new Environmental Assessment for a proposed vegetation management project, and the District Ranger has expressed interest in applying some of the models described herein to inform that process.

Second, we developed a pilot questionnaire to identify the highest priority data and information needs to support decision-making related to planning and monitoring. The questionnaire assessed:

1) the types of spatial and non-spatial monitoring information that PSICC and ARP managers collect and use in planning, monitoring, and adaptive management;

2) other spatial data, and at what scales that data, is relevant for planning, monitoring, and adaptive management.

3) the barriers to accessing and using data and analytical tools to inform decision-making

We piloted this questionnaire with seven resources specialists, which were selected by the Forest Planner and Natural Resources Staff Officer at the PSICC, from the following program areas: Range; Water, Air, and Soil; Fire and Fuels; Timber; Ecology; Recreation; Fisheries. We intend to present preliminary findings to the PSICC Planning and Renewable Resources group in February 2021 in an open session with other resource specialists and personnel to identify next steps, e.g., whether additional interviews are warranted.

Third, CFRI is in the process of developing a CFRI Geospatial Portal, a spatial data portal and map viewing platform to help inform management decisions at multiple scales. The geospatial portal will have multiple components or modules, developed independently but working in parallel with one another. We plan to develop a CFRI Data Viewer where CFRI will be hosted, displayed, and available for download. We will also develop a curated list of spatial datasets maintained by others that our partners may find useful for forest restoration. We would also like to develop a US Forest Service planning data section, with spatial data that directly informs Forest Plan revision, biennial monitoring and evaluation reporting, and landscape-scale planning efforts for the Arapaho Roosevelt and Pike San Isabel National Forests. The needs assessment pilot described above is the first step in identifying types of data the PSICC uses for planning and monitoring, limitations of such data, and additional data and information needs to better integrate best available science and information into Forest planning and monitoring. Continued collaboration with the Forest Planner and PSICC Planning and Renewable Resources group will be necessary to build off initial findings and develop a geospatial portal that is useful and useable.

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Appendix A. Monitoring Across Scales

Table A1. Monitoring across scales. Key attributes and the monitoring approach are identified in RMRS-GTR-373 for stand-scale effectiveness monitoring. Metrics are those stand-scale metrics collected across the PISCC at projects managed by the Forest Service or CFRI. Abbreviations: FIA, Forest Inventory and Analysis; CSE, Common Stand Exam; F2F, Forests2Faucets; USPP, Upper South Platte Partnership; WRRG, Wildfire Risk Reduction Grant; CFLRP, Collaborative Forest Landscape Restoration Program; SRLCC, The Southern Rockies Landscape Conservation Cooperative.

Stand-Scale Monitoring - At the stand scale, monitoring uses a plot-based sampling approach that collects information on key attributes of stand structure and composition								
KEY ATTRIBUTE	***GTR-373 Approach***	**METRICS**	**Monitoring Effort***					
			Forest Service		**CFRU (Plot design name: projects implemented)**			
			FIA	**CSE**	**Simple Plot: (1) F2F (2) USPP (3) WRRG**	**Mothership: (1) CLFLRP (2) F2F**	**CFLR Understory: (1) CFLRP**	**SRLCC: (1) CFLRP**
plot character	*qualitative photo and/or description of plot*	photo	X	X	X	X	X	X
tree density	*the number of trees per ground area, typically expressed as trees per acre as well as by basal area. Plot-based monitoring can measure tree density within fixed-area plots (simply as the count of trees within the plot), or in variable-radius plots using a basal area prism.*	canopy density			X	X	X	X
		sapling diameter (DBH)	X	X	X	X		X
		tree diameter (DBH)	X	X	X	X	X	X
		trees per acre	X	X	X	X	X	X
		tree seedlings	X	X	X	X	X	X
		tree species per acre	X	X	X	X	X	X
species composition	*represents the relative proportion of different tree species within a stand.*	sapling species	X	X	X	X		X
		sapling status at present	X	X	X	X		X
		tree damage	X					
		tree species	X	X	X	X	X	X
		tree status at present	X	X	X	X	X	X

tree size distribution	*tree size distributions by size classes constructed from tree diameters and heights are measured as part of the density sample.*	sapling diameter (DBH)	X	X	X	X		X
		sapling height	X	X	X	X		X
		tree diameter (DBH)	X	X	X	X	X	X
		tree height/length	X	X	X	X	X	X
tree age distribution	*tree age distributions can be constructed if trees in the density sample are cored and aged. Old trees (>150 years old) can also be qualitatively assessed based on morphological characteristics.*	tree age	X	X				
		tree seedlings	X	X	X	X	X	X
spatial heterogeneity	*the spatial distribution of trees within the stand, often characterized by tree groups, scattered individual trees, and openings. Plot- or transect-based approaches can be used here as well, whereby openings, tree groups, and single individual trees are characterized according to relative proportion and spatial patterns.*	canopy density			X	X	X	X
		tree group size			X	X		X
surface fuel loads	*the amount of woody material on the forest floor, typically characterized by size class (1-, 10-, 100-, and 1000-hour fuels) as well as litter and duff depths. Surface fuels can be characterized using Brown's transects (Brown et al. 1982) or the photoload technique.*	1000-hr fuels		X	X	X		
		biomass collections			X	X		
		course woody debris	X	X	X	X		
		course woody debris decay class	X	X	X	X		
		fine woody debris/ fuels	X	X				
		jackpots/burn piles	X		X	X		
		litter/duff depth	X	X	X	X	X	X
		photoload			X	X		

fire behavior	*surface fuels and other stand attributes can be linked to fire behavior models to predict changes in fire behavior due to treatment. Fire behavior metrics may include flame lengths, rates of spread, fireline intensity, and crowning index.*	sapling canopy base height			X	X		X
		sapling diameter (DBH)						
		tree compacted crown ratio	X					
		tree crown base height		X	X	X		X
		tree diameter (DBH)						
		tree uncompacted crown ratio	X					
understory vegetation	*describes the amount and types of plants below the forest canopy. Primary vegetation functional groups are graminoids, forbs, and shrubs. Understory vegetation cover by functional groups or species can be measured along transects using quadrat, point-intercept, or line-intercept approaches.*	invasive plant cover ocular estimate	X	X				
		live vegetation cover by functional group	X	X				
		understory forest floor substrate - line point intercept		X		X	X	X
		understory forest floor substrate - ocular estimate			X			
		understory shrub cover		X	X			
		understory species presence				X	X	X
		understory species presence				X	X	X
		understory vegetation cover - line point intercept		X		X	X	X
		understory vegetation cover - ocular estimate			X			

Table A2. Supplemental description table of stand-scale monitoring metrics, description of method, and the projects managed by the Forest Service and/or CFRI where each metric was implemented. Metrics listed reflect metrics listed in Table A1. Abbreviations: FIA, Forest Inventory and Analysis; CSE, Common Stand Exam; F2F, Forests2Faucets; USPP, Upper South Platte Partnership; WRRG, Wildfire Risk Reduction Grant; CFLRP, Collaborative Forest Landscape Restoration Program; SRLCC, The Southern Rockies Landscape Conservation Cooperative.

Metric	Method Description	Monitoring Effort*					
		Forest Service		CFRU (Plot design name: projects implemented)			
		FIA	CSE	Simple Plot: (4) F2F (5) USPP (6) WRRG	Mothership: (1) CLFLRP (2) F2F	CFLR Understory: (1) CFLRP	SRLCC: (1) CFLRP
1000 hr fuels	*Measure length and end diameters of all 1000hr fuel logs (>3in diameter) and record status (rotten or sound)*		X	X	X		
Biomass Collections	*Oven dry weight of fuel collected*			X	X		
Live vegetation cover by functional group	*Estimate canopy cover by height layer (0-2ft, 2.1-6ft, 6.1-16ft, >16ft) of each structure growth habit (Trees, shrubs/ subshrubs, forbs, graminoids)*	X					
Canopy density	*Densitometer scope at every foot along transect*			X	X	X	X
Course woody debris (CWD)	*Tally a piece if it is >3.0 inches in diameter at the point of intersection with the transect*	X	X	X	X		
CWD decay class	*Indicate decay class of each piece*	X		X	X		
Crown class	*Rate tree crown*	X	X				

CWD length	*Record the code that indicates whether the CWD total length is less than 3 feet long (and at least 0.5 foot long)*	X	X				
Diameter of hollow at point of intersection	*Diameter of hollow at the point of intersection*	X	X				
Fine woody debris/fuels	*Tally of pieces per size class along transect*	X	X				
General plot character	*Photo(s)*	X	X	X	X	X	X
Invasive plant cover	*Estimate percent cover of listed invasive species*	X	X				
Jackpots/burn piles	*Record length, width, and height of piles*	X		X	X		
Litter/duff depth	*Average depth of litter and duff*	X	X	X	X	X	X
Photoload	*Ocular estimate of fuel loading for 1-hr, 10-hr, 100-hr fuels*			X	X		
Sapling crown base height	*Lowest height of continuous live vegetation*			X	X		X
Sapling diameter (DBH)	*Diameter at breast height (4.5 feet)*	X	X	X	X		X
Sapling height	*Field measured height/length from ground level*	X		X	X		X
Sapling species	*Sapling species identification*	X	X	X	X		X
Sapling status at present	*Classify standing saplings as live, dead and/or decay status (recently dead, snags and/or rotten)*	X	X	X	X		X
Tree age	*Bore tree at DBH*	X	X				

Tree compacted crown ratio	*Ratio of live crown length to actual length*	X					
Tree crown base height	*Lowest height of continuous live vegetation*		X	X	X		X
Tree damage	*Record damage agents for tree*	X	X				
Tree diameter (DBH)	*Diameter at breast height (4.5 feet)*	X	X	X	X	X	X
Tree group size	*Measure of distance (start and stop) and number of trees covered by closed-canopy forest areas versus openings along transect.*			X	X		X
Tree height/ length	*Field measured height/length from ground level*	X	X	X	X	X	X
Tree seedlings	*Number of individuals by species; classified by height (CFRI) or conditions (FIA)*	X	X	X	X	X	X
Tree species	*Tree species identification*	X	X	X	X	X	X
Tree status at present	*Classify standing trees as live, dead and/or decay status (recently dead, snags and/or rotten)*	X	X	X	X	X	X
Tree uncompacted crown ratio	*Ratio of compacted live crown length (less than 2-foot spacing) to actual length*	X					
Understory forest floor substrate	*Line point intercept. Record forest floor substrate along transect (litter/duff, soil/gravel, rock, fine fuels, coarse fuels, moss/lichen, woody basal, herbaceous vegetation basal)*		X		X	X	X

Understory forest floor substrate	*Ocular estimate measure of ground cover class of floor substrate (litter/duff, soil/ gravel, rock, fine fuels, coarse fuels, moss/lichen, woody basal, herbaceous vegetation basal) to nearest percent in subplot*		X	X			
Understory shrub cover	*Line point intercept cover of live shrub layer only*		X	X			
Understory species presence	*List of all plant species at plot*				X	X	X
Understory vegetation cover	*Ocular estimate measure of ground cover class to nearest percent*		X	X			
Understory vegetation cover (including shrubs)	*Line point intercept; Record vegetation to species level*		X		X	X	X

**Although similar metrics were collected at one or several of these projects, protocol adjustments and collection methods may have changed over time so that data may not be necessarily comparable between projects without adjustments or additional analysis.*

Table A3. Brief list of the landscape-scale models/tools implemented by CFRI. Key attributes and the monitoring approach are identified in RMRS-GTR-373 for landscape-scale effectiveness monitoring. Table provides an overview of the inputs required to run the models, and Includes inputs typically used by CFRI; however, similar inputs may be substituted if they meet similar criteria. Inputs may require extensive processing before input into the model. Extent represents the recommended or typical spatial extent of the analysis.

Landscape-Scale Monitoring -
At the landscape scale, metrics are concerned with vegetation pattern and its influence on landscape-level ecological processes such as fire behavior and watershed function.

Key Attribute	GTR-373 Approach	Model	Inputs	Extent
landscape spatial heterogeneity	*Landscape spatial heterogeneity is the spatial pattern and juxtaposition of vegetation patches and openings and other landscape features.*	Canopy Cover Imagery Classification	Worldview or Quickbird 3-m resolution imagery	project
		Restoration Simulator (RestSIM)	LANDFIRE baseline fuels	large landscape
			Soil moisture index (topographic wetness index and solar radiation)	
			Desired canopy cover and variability (based on historical density and canopy cover from available literature)	
landscape fire behavior	*Landscape vegetation patterns can be tied to landscape fire behavior through spatial fire models. Predicted changes in landscape fire behavior (including crown fire activity, flame lengths, fireline intensity, rates of spread, and spotting distances) due to treatments can then be evaluated.*	Potential Fire Behavior - Forest Vegetation Simulator Fire and Fuels Extension (FVS-FFE)	Tree/stand survey data	project; stand
		Risk Assessment for Priority Investment Decision Support (RAPIDS)	Fire hazard rasters derived from FlamMap, LANDFIRE baseline fuels, and RAWS weather scenarios	large landscape
			Highly valued resources and assets (HVRA) spatial data	
			Local/project-specific response functions to characterize HVRA vulnerability to fire, and relative importance weights to represent community values	
			Reference spatial data (landscape spatial data such as: project extent, major roads/streams, hillshade, and topography, etc.)	

watershed function	*Watershed function represents the capture, storage, and release of water within a watershed with subsequent effects on the transport and distribution of materials such as soil and woody debris within the watershed. Specific indicators of watershed condition include such attributes as water quality, aquatic habitat and biota, and riparian vegetation.*	Risk Assessment for Priority Investment Decision Support (RAPIDS)	Fire hazard rasters derived from FlamMap, LANDFIRE baseline fuels, and RAWS weather scenarios	large landscape
			Highly valued resources and assets (HVRA) spatial data	
			Local/project-specific response functions to characterize HVRA vulnerability to fire, and relative importance weights to represent community values	
			Reference spatial data (landscape spatial data such as: project extent, major roads/streams, hillshade, and topography, etc.)	
		Revised Universal Soil Loss Equation (RUSLE)	Fire hazard rasters (crown fire activity) derived from FlamMap, LANDFIRE baseline fuels	large landscape
			Soil Survey Geographic Database (SSURGO)	
			30-m DEM	
			Landcover - LANDFIRE Existing Vegetation Type (EVT)	

Appendix B. Forests2Faucets project example summary update report

COLORADO FOREST RESTORATION INSTITUTE | COLORADO STATE UNIVERSITY

Forests to Faucets Monitoring Summary
Little Morrison

Goals and Objectives:

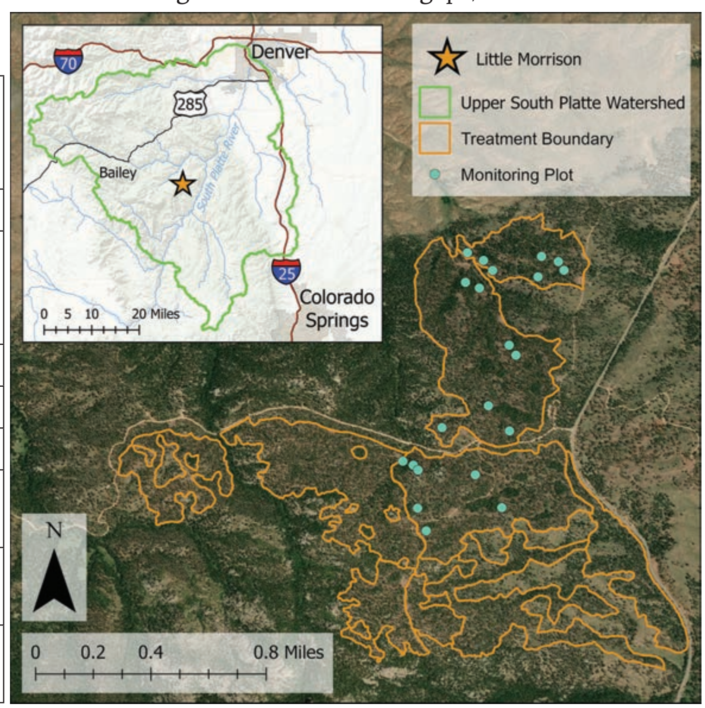
The main objective of the Forests to Faucets partnership between Denver Water and the U.S. Forest Service is to reduce wildfire risk to Denver's critical watersheds and improve forest conditions across the Front Range. Forest restoration treatments in the Upper South Platte were designed to create a mosaic pattern across the landscape that promotes wildlife habitat and resilience to fire, insects and disease. To achieve the mosaic pattern, stand prescriptions aimed to reduce overall canopy cover and tree density, while increasing variability in stand age and forest openings. Targets for Little Morrison include reducing basal area to an average of 25 - 50 ft^2, and tree density to 50-60 trees per acre. Ponderosa pine and larger trees of all species were to be favored for retention in varying group sizes from 2 trees to 50+ trees in reserves.

Highlights:

Most metrics suggested that stand conditions were closer to desired conditions following treatment. However, because thinning intensity at Little Morrison was relatively light, future treatments may be needed to achieve desired conditions and ensure treatment longevity. It should be noted that the project was mostly on a gentle, north facing slope. While the potential for high intensity crown fire was slightly reduced, passive crown fire was still predicted under moderate weather conditions following treatment. Thinning created more forest gaps, but there was no change in gap size variability.

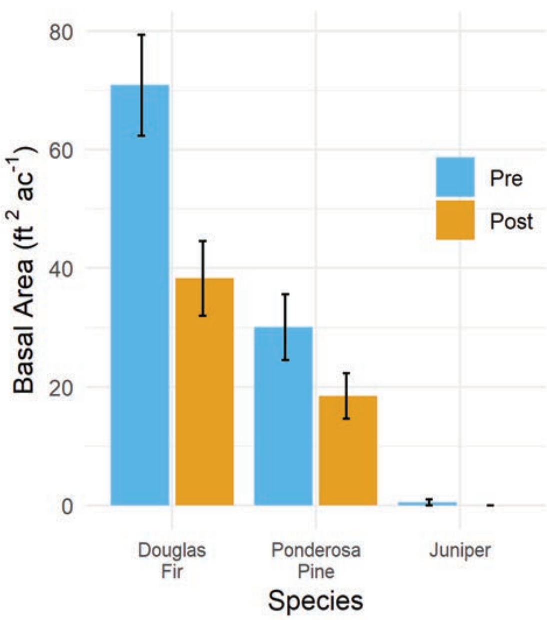
Project Information

Implementation Agency	Pike San Isabel National Forest, South Platte Ranger District
Ownership	U.S. Forest Service
Funding	Collaborative Forest Landscape Restoration Program
Year Completed	2018
Acres Treated	615
Acres Monitored	290
Forest Type	Ponderosa Pine Mixed Conifer
Implementation method	Mechanical thinning
Slash treatment	Product removal and pile burning

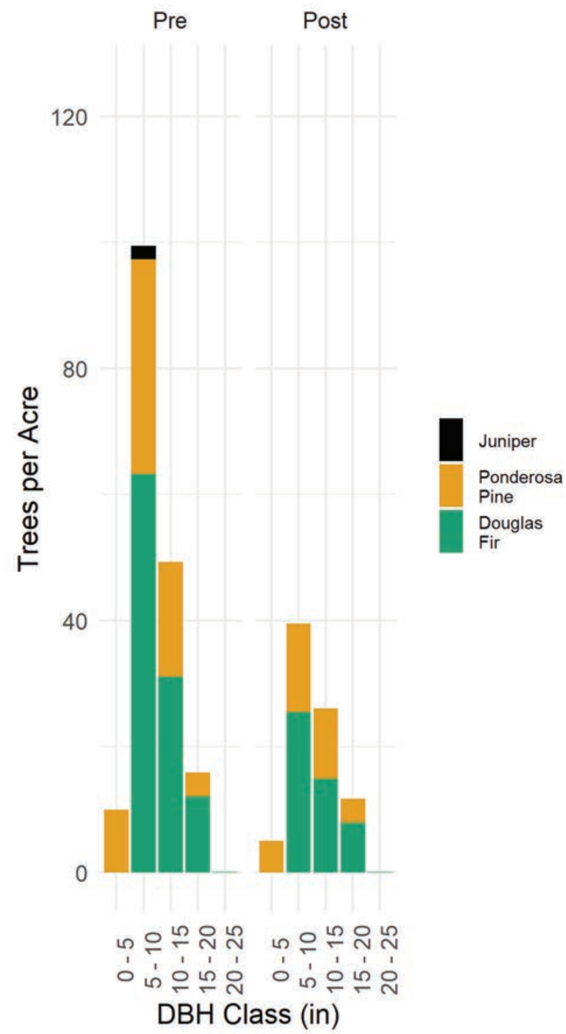


Stand Structure and Composition

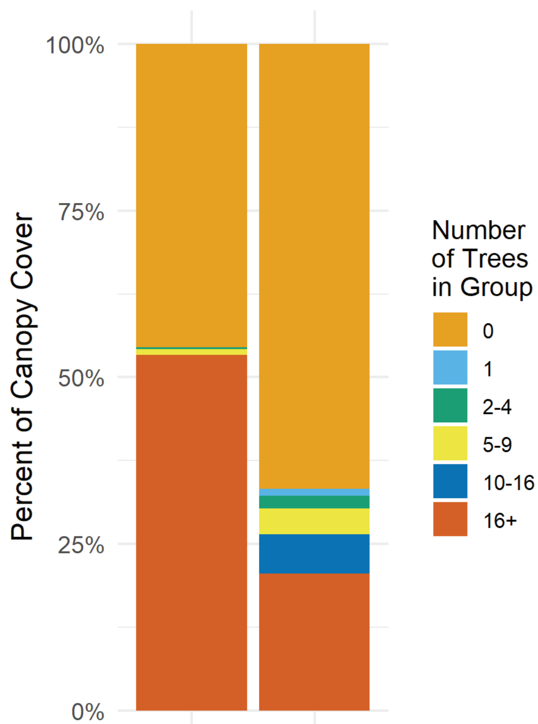
Change in basal area by species



Change in tree size distribution



Change in canopy cover by tree group size



Methods: Data was collected on the ground from 22 plots to assess the changes in stand structure and composition.

Highlights: Forest thinning reduced tree density by 37%, basal area by 44%, and canopy cover by 17%. Stand composition shifted marginally to favor ponderosa pine and larger trees, and there were more small and medium tree groups after treatment. Future thinning could break up residual large tree groups to further increase heterogeneity and reach targets for tree density and basal area.

Stand characteristics pre- and 1 year post-treatment

Phase	Trees per Acre	Basal Area (ft^2/ac)	Canopy Cover (%)	Seedlings per Acre	Percent Ponderosa by BA	Quadratic Mean Diameter	Crown Base Height (ft)
Pre	504 ± 156	101 ± 5	49 ± 4	1815 ± 485	20	7.7 ± 0.6	12.5 ± 1.1
Post	322 ± 128	57 ± 6	32 ± 5	1485 ± 454	33	9.0 ± 1.0	13.3 ± 1.1

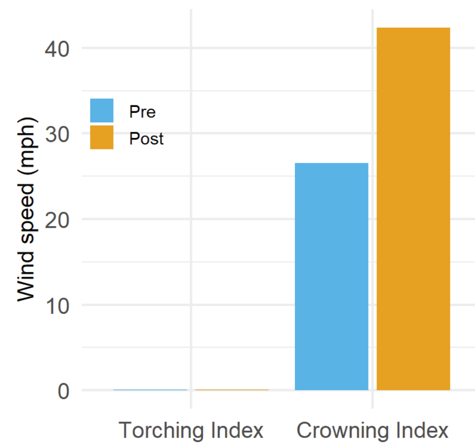
Surface Fuel Conditions and Potential Fire Behavior

Surface fuel conditions pre- and 1 year post-treatment

Phase	Fine Woody Fuel Loading (tons/acre)	Coarse Woody Fuel Loading (tons/acre)	Litter Depth (in)	Duff Depth (in)	Shrub Cover (%)
Pre	1.07 ± 0.17	1.92 ± 0.68	9.03 ± 1.22	0.83 ± 0.07	0.92 ± 0.09
Post	1.12 ± 0.17	3.06 ± 0.76	4.95 ± 1.06	1.13 ± 0.16	0.57 ± 0.08

Modeled fire behavior pre- and 1 year post-treatment

Phase	Pre		Post	
Fire Weather Conditions	Moderate	Severe	Moderate	Severe
Fire Type	Passive	Passive	Passive	Passive
Total Flame Length (ft)	3.5	29.8	3.4	15.0
Surviving Tree Basal Area (%)	45	1	57	2



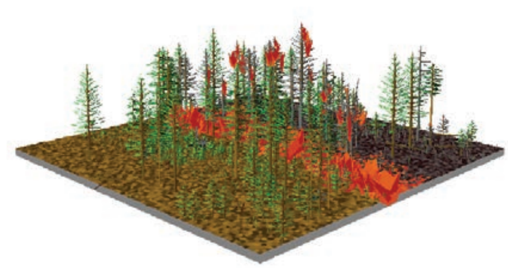
The figure above shows the wind speed needed to initiate crown fire activity or torching (torching index), and the wind speed needed to carry an active crown fire (crowning index).

Methods: To model the potential fire behavior pre- and post-treatment, field data was used with the Fire and Fuels Extension to the Forest Vegetation Simulator.

Highlights: Surface fuel accumulations were limited following treatments and fine fuels were unchanged. The crowning index increased by 62% and the predicted total flame length was cut in half under severe weather conditions. However, following treatment passive crown fire was predicted to occur under moderate weather conditions, the torching index did not increase from zero, and the potential for high intensity fire behavior remains high. Additional treatment may be required to support the use of prescribed fire at Little Morrison.

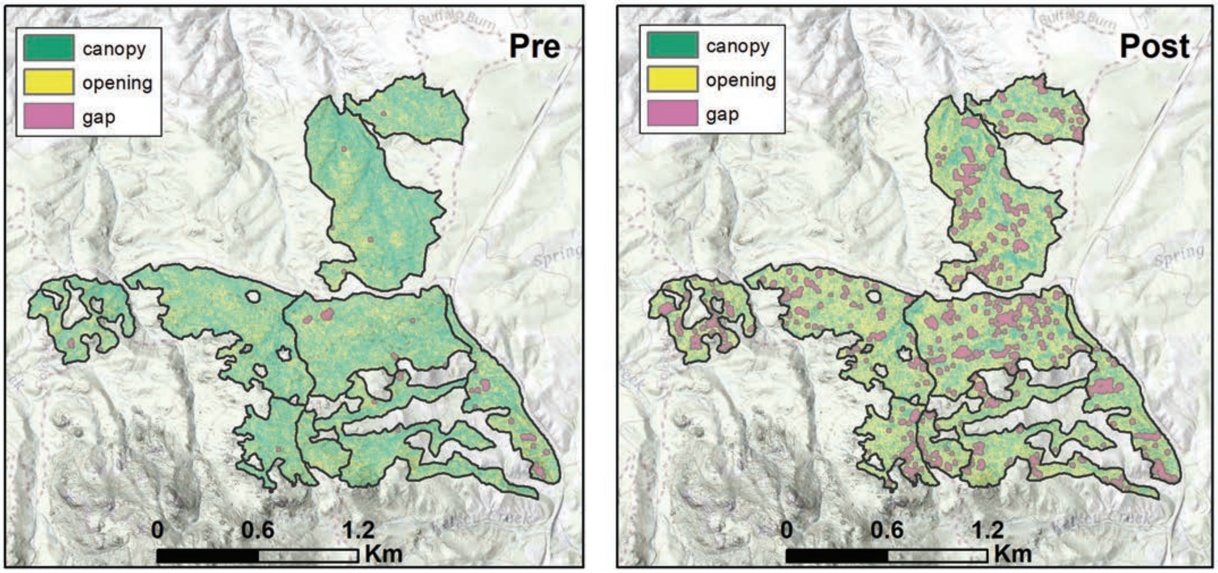
Pre-Treatment | ***1 Year Post-Treatment***

During Fire

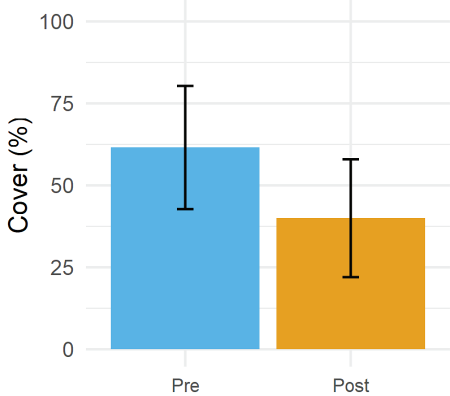


After Fire

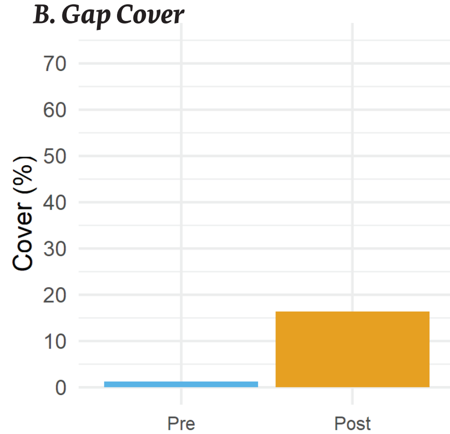
Spatial Heterogeneity



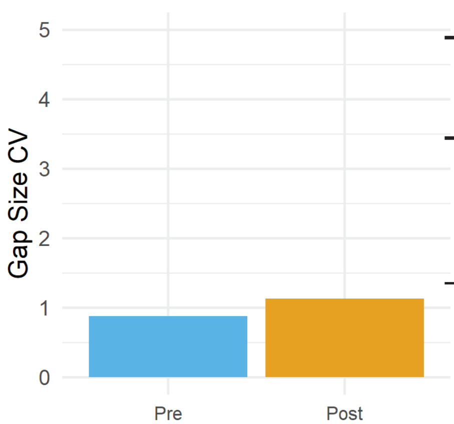
A. Remotely Sensed Canopy Cover



B. Gap Cover



C. Gap Size Variability



Changes in spatial heterogeneity pre- and 1 year post-treatment

Phase	Mean Gap Size (acres)	Gap Size Range (acres)	Median Shape Index
Pre	0.30	0.07 - 0.91	0.98
Post	0.42	0.07 - 3.36	0.97

Methods: To analyze spatial heterogeneity, changes in canopy cover and forest gap characteristics were measured by classifying satellite imagery before and after treatment.

Canopy Cover (A) is the percent area within the project boundary covered by forest, and **Gap Cover (B)** is the percent area covered by a gap*. **Gap Size Variability (C)** describes gap size diversity, and is measured as the coefficient of variation; higher values indicate that gaps vary more in size.

Highlights: Gap coverage increased following thinning, but there are still relatively few gaps and the variability in gap size and shape was unchanged.

**A gap was defined as an area larger than .11 acres with less than 5% canopy cover.*