Proposal Number/Title: 23-2-01-10: Using landscape features, plot measurements, and remote sensing data to improve predictions of fuels treatment longevity in the Colorado Front Range
Principal Investigator Name and Affiliation: David Barnard, USDA-ARS

I. Technical background. Wildfires are increasing in size and severity across the western US due to changes in climate (Abatzoglou and Williams, 2016), land use, and management (Prichard *et al.*, 2021), and this trend is expected to continue (Moritz *et al.*, 2012; Coop *et al.*, 2022). Already, the United States has seen a fivefold increase in suppression costs since the mid 1980's (NIFC, 2022), as well as an increasing number of post-fire regeneration failures and ecosystem state changes from forest to non-forest ecosystems (Davis *et al.*, 2019). These disruptive forces highlight an increasing need for managers to mediate the ecological impacts of severe and possibly transformative fires, while also reducing socioeconomic impacts (Mietkiewicz *et al.*, 2020), and suppression costs (Prichard *et al.*, 2021).

One of the ways to accomplish many of these economic and ecological goals is by fuel reduction treatments. Fuel reduction treatments use mechanical, biological, and chemical thinning, and prescribed fire to change the ecosystem's structure by reducing overall fuel loads, increasing heterogeneity or reducing specific components, like surface or ladder fuels (Agee and Skinner, 2005). Typical treatment goals include reducing the potential for high fire severity, tree mortality, and crown scorch (Kalies and Yocom Kent, 2016). The increasing need for fuel treatments are highlighted by the US Forest Service having recently committed to fuel treatments on 50 million acres of federal and private land by 2032 (USFS 2022). However, defining treatment effectiveness is challenging as it differs among management agencies and across treatments, thus limiting comparison among treatments over space and time. This is because treatments may have unique social and ecological goals, and areas with different initial conditions might require different treatments to achieve the same goals. Hence there is a clear need to improve understanding of how these goals vary with treatment type, site conditions, and climate.

There is an emerging consensus that thinning followed by the removal of surface fuels, either mechanically (Briggs, Fornwalt and Feinstein, 2017) or via prescribed burn treatments are broadly effective at reducing fire severity (Fulé *et al.*, 2012; Martinson and Omi, 2013; Kalies and Yocom Kent, 2016; Cansler *et al.*, 2022). However, much uncertainty remains about the effectiveness of single treatment strategies. Thinning or prescribed fire alone can reduce surface, ladder and/or canopy fuels and mitigate wildfire severity (Pollet and Omi, 2002; Prichard and Kennedy, 2014; Prichard *et al.*, 2020). However, singular treatments may have limited efficacy because they only target one fuel type. For example, thinning without surface fuel management can increase surface fuels after treatment (Martinson and Omi, 2013; Cansler *et al.*, 2022), which can lead to higher intensity surface fire, greater soil heat flux, and increased adult tree mortality (Stephens *et al.*, 2009; Prichard and Kennedy, 2012). Thinning treatments can be more effective if they have specific structural goals like increasing canopy base height and reducing canopy bulk density (Harrod *et al.*, 2009). But most studies of treatment effectiveness study only one fire or one treatment project (Kalies and Yocom Kent, 2016), and so they cannot effectively account for variation in climate, soil, topography, or understory vegetation.

Topographic position and disturbance history are primary drivers of forest productivity, biomass, and understory characteristics, especially in complex mountainous terrain (Barnard, Barnard and Molotch, 2017; Swetnam *et al.*, 2017). South-facing slopes are typically warmer and drier, with more understory surface fuels and lower tree density, while north-facing slopes are typically the opposite. As climate warms, increased aridity reduces fuel moisture and decreases the capacity for plants to grow (Yuan *et al.*, 2019; Grossiord *et al.*, 2020) such that the understory may lose its connectivity and become fuel-limited.

South-facing sites may have a sufficiently warm microclimate that seedlings for species such as *Pinus ponderosa* can no longer establish (Rother, Veblen and Furman, 2015), highlighting the importance of treatments at these sites since post-fire restoration is unlikely to be successful especially in cases where high-severity fire kills seed stock from non-serotinous species.

Despite growing understanding of how ecological processes vary across landscapes, there is still high uncertainty regarding how long fuel treatments will remain effective. Most of the benefits of thinning are documented in areas that burn a few years after the treatment was conducted (Kalies and Yocom Kent, 2016), but less than 1% of thinning treatments ever encounter a fire during the first 10 years after a treatment (Odion and Hanson, 2006; Baker and Rhodes, 2008; Barnett *et al.*, 2016; Kolden, 2019). This indicates the need for longer-term treatment effectiveness forecasts in order to inform the frequency of retreatments necessary to maintain efficacy (Krofcheck *et al.*, 2017; Vaillant and Reinhardt, 2017), especially since some sites might only see a 5-10 year reduction in expected burn severity following thinning and 15 years following prescribed fire (Cansler *et al.*, 2022). Long-lasting treatments are most desirable due to resource limitations, therefore improved understanding of longevity will assist managers to plan resources for future retreatment needs and limit large fires from overwhelming fuel treatment areas and impacting effective suppression (Agee *et al.*, 2000; Finney, 2000).

While most fuel treatment research has focused on tree density and basal area, it is poorly understood how surface fuels, shrubs, grasses and forbs accumulate, interact and affect fire behavior. This limitation is further complicated by poor understanding of how these fuels respond to fire severity, soil type, a warming climate, changing precipitation patterns, and spread of invasive species (Kalies and Yocom Kent, 2016; Kerns *et al.*, 2020). The effects of understory plants on fire behavior also changes through time, as tree seedlings and shrubs inevitably grow larger, increase vertical fuel continuity and progressively increase the capacity of a surface fire to transition into the canopy. Interactions between tree seedlings and understory plants contribute additional uncertainties in tree regeneration and ladder fuel development, since they compete directly for moisture and light (Young *et al.*, 2019; Wooten *et al.*, 2022). Thus, it will be critical that future modeling frameworks account for the interactions between grass, forb, tree seedling and shrub establishment that drive fire behavior.

Understanding understory fuel accumulation is essential to maximizing treatment longevity. Understory plants may be short enough to not contribute to surface-to-crown fire transition, while at the same time limiting the establishment of tree seedlings and shrubs (Madany and West, 1983). Concurrently, these same plants can provide sufficient fuel connectivity (Archibald, Staver and Levin, 2012) to carry frequent surface fires that serve to keep ladder fuels at a low density. These conditions may also contribute to increased ease and safety for prescribed fire operations by enhancing burn coverage while reducing holding concerns due to lower spotting potential and short fire residence times.

In order for fuel reduction treatments to be an effective tool in managing forests in the face of all of the challenges forests are confronted with in the near future, it is important to maximize treatment longevity. Here, we propose to complete remeasurement of a broad network of 316 plots in 21 treatment projects >10 years after initial treatment to complement previously completed pre- and post-treatment surveys. The work proposed here will use the data to quantify fuel accumulation over time, model the resulting potential fire behavior, and use this information in conjunction with what we learn from stakeholders to understand the longevity of current and future fuel treatment effectiveness. Understanding the site characteristics and climate conditions necessary for treatments to have lasting effectiveness will allow land managers to maximize their return on investment by selecting the optimal treatment type, location, and maintenance frequency (Agee and Skinner, 2005; Barros *et al.*, 2018)**.**

II. Methods

1. Study design

The proposed work will capitalize on a unique dataset of pre- and post-treatment sampling of fuels and vegetation from three previously published fuels treatment studies (Table 1). All plots were measured within one year before and after treatments, and will again be measured 10 years after treatments. Most sites (~200) also include intermediate (2-7 year) measurements (Fig. 1). These study sites include treated sites (e.g. thinning and prescribed fire) paired with untreated controls throughout central and northern Colorado (Fig. 2). We will focus on the following three objectives: **Objective 1: Develop a large dataset of long term post-treatment monitoring and quantify landscape and climate drivers of site-to-region-scale patterns of fuels accumulation and vegetation change after fuel treatments.** The spatial distribution of treatment areas in our dataset represents a gradient of landscape characteristics which, when combined with the progression of treatments and sampling over time, capture various site characteristics, fuel treatment characteristics, and climate patterns. This provides a unique opportunity to develop a deeper understanding of fuel accumulation, vegetation change, and subsequent impacts on ecological processes as driven by landscape and climate factors. Moreover, this expanded analysis may provide additional insight into ecological functioning and landscape processes that can be integrated into existing models and decision support tools. **Objective 2: Evaluate approaches to defining treatment effectiveness and longevity as a function of fire behavior changes.** We argue the lack of a universal definition of treatment effectiveness complicates comparison among studies, sites, and over time which will inhibit progression of the science and how well it can be applied in operational capacities. We will work with stakeholders (local conservation districts and cooperatives; see letters of support) to identify desirable potential fire behavior outcomes (e.g. crown fire activity, tree mortality, fire severity) as constrained by operational limitations (e.g. budget, private landowner participation). We will use these outcomes in conjunction with an analysis of our dataset and modeling simulations of behavior (Forest Vegetation Simulator (FVS); Dixon 2002) over time to define more broadly applicable thresholds for treatment effectiveness and compare those thresholds to more standard approaches. **Objective 3: Improve understanding of treatment longevity and how it may change in the future, in order to inform the frequency and type of treatments needed to maintain treatment effectiveness.** Having quantified controls on vegetation growth and fuels accumulation (Objective 1), and thresholds for treatment effectiveness from fire behavior modeling (Objective 2), we will then develop predictive spatial models of the longevity of current and future fuels treatments given treatment type, landscape characteristics, site conditions, and mean observed or forecasted climate.

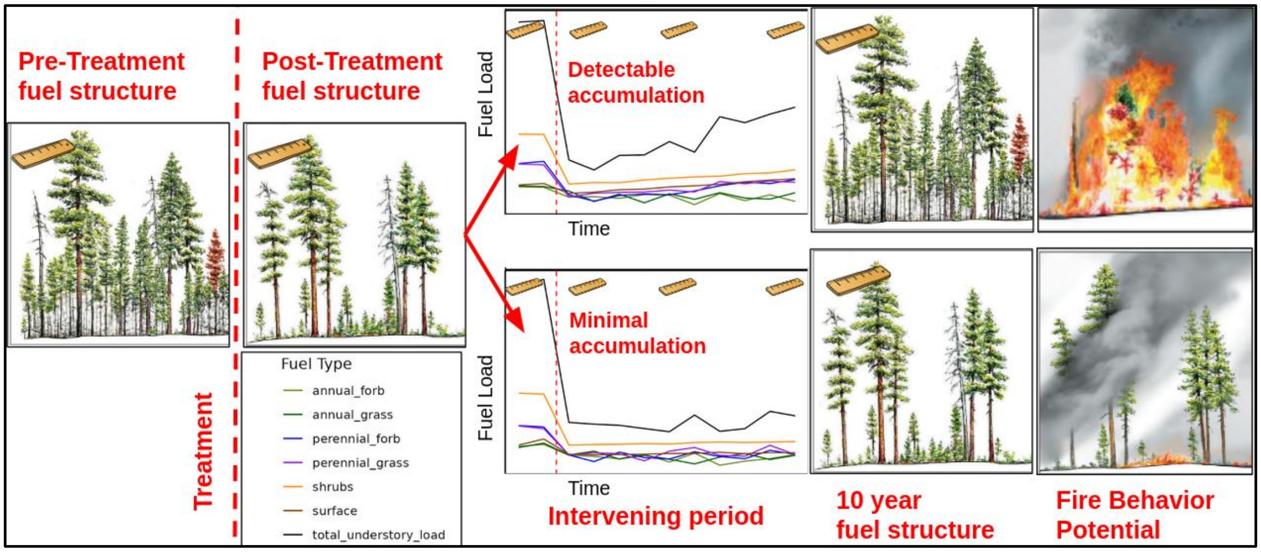

Figure 1. Standardized measurements were made before and after treatments, and in many cases 5 years after treatments. The proposed work will complete the 10-year post-fire measurements at all plots, and conduct modeling to understand the fuel accumulation and potential fire behavior over time. Images modified from Prichard et al. 2021.

Table 1: Datasets for sites with fuel structure measurements immediately before and after fuel treatments, that have either already been measured ten years post treatment, or will be in the next few years with the proposed work. Abbreviations: Collaborative Forest Landscape Restoration Program (CFLRP), Colorado Department of Natural Resources (DNR), Common Stand Exams (CSE).

Dataset	**Treatment Year**	**Treatment Projects**	**Plots**	**10 year post-treatment measurements**	**Citation**
DNR	2014-2015	11	85	85 Proposed 2025	(Morici *et al.*, 2019)
CFLRP	2011-2012	4	111	21 remeasured in 2022* 36 planned in summer 2023* 54 proposed for 2024	(Briggs, Fornwalt and Feinstein, 2017)
CSE	2012	6	120	120 Proposed 2024-2025	(Cannon *et al.*, 2018; Barrett *et al.*, 2021)

** already funded*

2. Study Sites and Sampling Design

The dataset we will use for this project is a composite of three previously published efforts (Table 1). It includes 316 plots in 21 treatment projects across central and northern Colorado that were treated between 2011-2015 (Figs. 2 & 3). This dataset also includes 15 plots treated in 2011-2012 that burned over a range of severities in 2020 during the Calwood fire. The few that burned at low severity may be analyzed for retreatment effects. Treatments completed in 2014 and 2015 will be resampled during the summers of 2024 and 2025, respectively, to meet the 10 year threshold for long-term treatments defined in the FOA. Fuel treatment types included hand thinning, mechanical thinning, mastication, and prescribed burns. Plots were selected for fuels and vegetation sampling (described below) within each treatment area and in

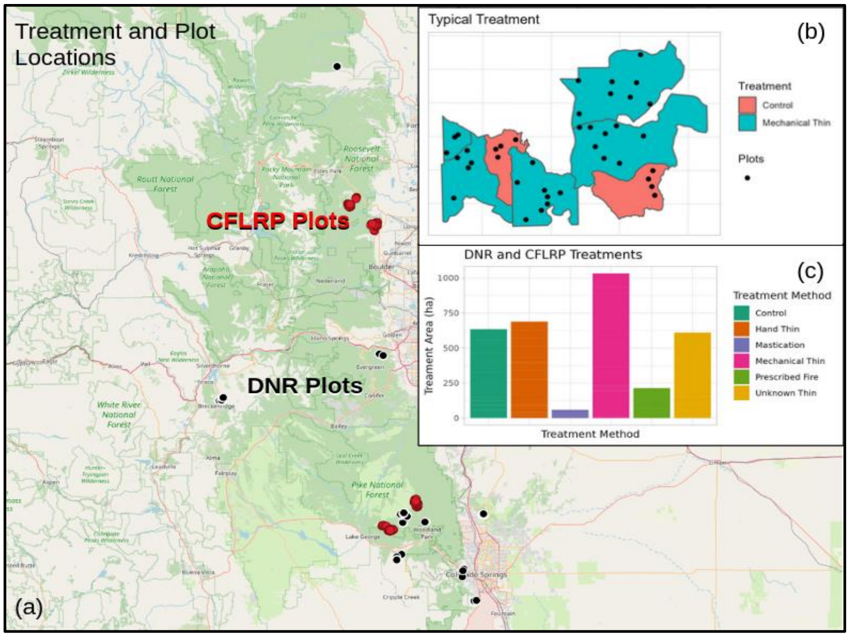

Figure 2. Treatment and plot locations of the DNR (black) and CFLRP (red) plots from the Colorado Forest Restoration Institute database. In (b) a typical treatment project is shown with field measurement plots. Area treated by treatment type is shown with field measurement plots. The area treated by treatment type is shown in (c).

adjacent untreated control areas (Fig 2b; Cannon et al. 2018). The area treated for datasets are shown in Fig. 2c and Fig. 3. Ten-year resampling has already been completed for 21 plots and an additional 36 plots will be sampled in the summer of 2023. The work we propose here will complete ten-year post-treatment resampling of the remaining 259 plots during the summers of 2024 and 2025.

3.Field Measurements

Field measurements at all sites were made using the following standardized protocols for vegetation and fuels characteristics. Tree size and density were measured by counting and measuring the diameter of all trees ≥2.5” diameter at breast height (DBH) in a variable radius prism plot (10 or 20 Basal Area Factor). Seedlings and saplings (<2.5” DBH) were counted in fixed radius 1/200 ac (8.3’ radius) plots. Tree height and canopy base height (CBH), canopy cover were measured using Common Stand Exam methods (US Forest Service 2022). Surface fuels (1/10/100/1000 hour fuel amounts and sizes, and litter and duff depths) were measured via two Brown’s transects (Brown, 1974). Grass, forb, shrub and and other ground cover components were measured on 3 50’ point-intersect transects extending from plot centers.

3. Data Analysis

We will create statistical models to quantify vegetation change and the accumulation of different fuel types (grasses, forbs, shrubs, tree seedlings, and adult trees) over time and in relation to a suite of climatic and landscape variables (Table 2). Because landscape and climatic factors can interact within sites and among treatments to affect a myriad of ecological processes (Germino *et al.*, 2018), we will develop models to test for effects of individual variables and variable interactions on outcome variables. For example, it may be beneficial to understand when seedling regeneration is inhibited by competition among fuel types (Madany and West, 1983) versus when it is inhibited primarily by climate. For regression model dependence, our plot sample size is 316 and we plan to analyze 13 potential predictors (Table 2), supplying a ratio of model predictors (P) to samples (n) > 24, which exceeds published recommendations ($P{:}n$ > 10) to avoid the so-called “*Large P, small n problem*” that can bias or invalidate

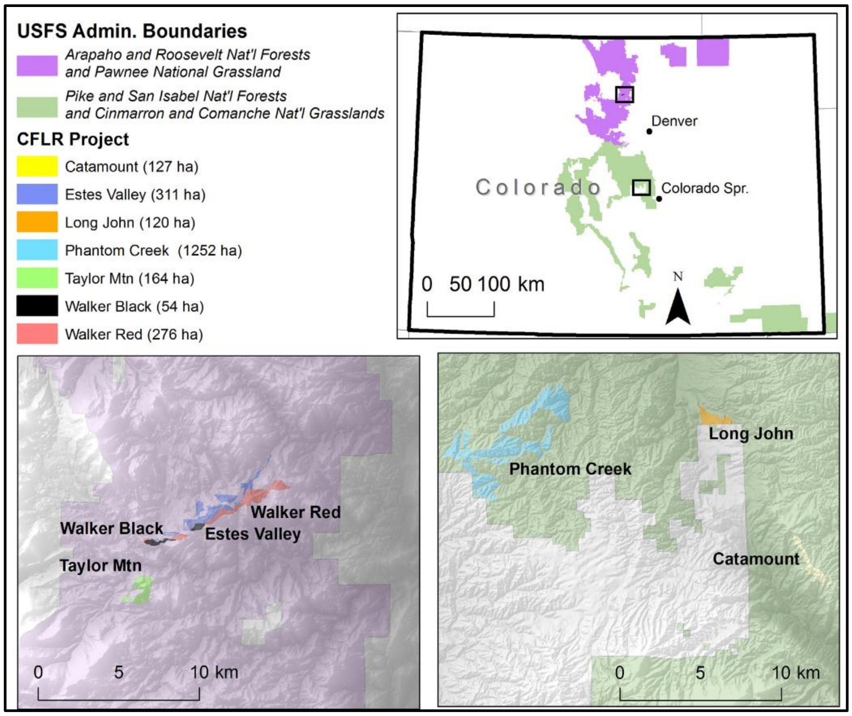

Figure 3. Treatment project locations and area treated for the CSE plots totaling 2304 ha (Cannon et al 2018).

model results (Bolker *et al.*, 2009; Barnard *et al.*, 2019). We conducted a preliminary power analysis to assess statistical differences among treatment areas and untreated controls and found that even when variables have small effect sizes, the sample size we would need for 90% power is only 214, well below our proposed sample size of 316. Finally, there is currently a lack of consensus in the literature regarding model selection for fuels accumulation and vegetation demographic changes post-treatment, so we will compare multiple approaches including machine learning, hierarchical and process-based modeling, including structural equation models (Rosseel, 2012; Lefcheck, 2016), demographic models (Davis, Higuera and Sala, 2018; Shriver *et al.*, 2019), joint species distribution models (Warton *et al.*, 2015; Tikhonov *et al.*, 2020), supervised machine learning (Barnard *et al.*, 2019), forest growth models (Dixon, 2002), and Bayesian multivariate response models (Bürkner, 2017). Model development and testing will be completed on different subsets of data to ensure proper assessment of model error and performance (Barnard *et al.*, 2019).

5. Fire behavior modeling and quantifying treatment effectiveness and longevity. We will use FVS with the Fire and Fuels Extension (Rebain *et al.*, 2010) to model vegetation growth and fire behavior at each site for pre- and post-treatment periods. The FVS model is an “individual tree, distance-independent, growth and yield model” which takes arguments of site capacity, tree size, and competition to estimate vegetation growth and fuel loads. The model can be run with observed climate or extended into the future using the FVS-Climate module which allows for a change in site capacity over time and climate projections from general circulation models. We will validate FVS output of vegetation growth and fire behavior against our field observations and reburned sites, respectively, which will be important to quantify confidence in FVS growth components and fire behavior, and as an essential bridge between the statistical modeling described in Objective 1 and the future forecasting described in Objective 3. We will also use the FVS model to define fire behavior potential and guide the development of treatment effectiveness and longevity estimates. As stated in the FOA, “baseline conditions may not be appropriate benchmarks for maintenance schedules,” and we cannot assume that treatments always improve fire behavior metrics. Given these two sources of uncertainty, we will define thresholds for treatment

Table 2. Landscape and climate datasets used as predictors of fuel accumulation and vegetation growth.

Variable/dataset	Description	Citation
Treatment Type	Type of fuel treatment	
SPEI	Multiscalar drought index	Vicente-Serrano, et al., 2010
NDVI	Vegetation greenness	
SSURGO soils	Soil data	NRCS, 2022
SSEBop ET	Evapotranspiration, site productivity	Senay *et al.*, 2013
Topographic wetness index	Topographic-based water inflow	Sørensen, Zinko and Seibert, 2006
Heat load	Index of solar radiation exposure	McCune and Keon, 2002
Environmental site potential	Vegetation type supported by biophysical environment at a given site.	Rollins, 2009
Climate data	Temperature, precipitation, humidity	Abatzoglou, 2013
Fuel moisture	1/10/100/1000 hour fuel moisture	Abatzoglou, 2013
Aspect	30m aspect from USGS	Gesch, 2002
Elevation	30m elevation from USGS	Gesch, 2002
Fire history	Pre-treatment wildfire occurrence	Eidenshink *et al.*, 2007

effectiveness in two ways: 1) a fixed manner i.e. avoidance of crown fire in 97th percentile weather, and 2) using a combined analytical and expert-opinion approach (through meetings with NCFC and stakeholders). For the combined analytical and expert-opinion approach, we will define a treatment as remaining effective by having reduced fire behavior metrics (e.g. flame length, rate of spread, crown fraction burned) *in comparison to nearby un-treated control areas over time*. The effectiveness threshold will then be quantified as the fuel and vegetation states at which fire behavior is statistically indistinguishable between treated and control plots, and treatment longevity will be estimated by the number of years that elapse post-treatment before fire behavior shows no statistical difference between control and treated plots. We argue it is important to test and compare these two different threshold approaches as the simplicity of the fixed approach may miss important fuel accumulation and vegetation change dynamics driven by climate and site characteristics that impact other aspects of fire behavior. We will then present the analytically defined thresholds to a broader group of forest and watershed managers and wildfire operations agencies that are part of the Northern Colorado Fireshed Cooperative (www.nocofireshed.org) for feedback on further threshold refinement.

6. Calculating the longevity of current and future treatments: We will use quantified landscape and climate controls on vegetation growth and fuels accumulation (Objective 1), and quantified thresholds for treatment effectiveness from fire behavior modeling (Objective 2) to develop predictive spatial models of the longevity of current and future fuels treatments given treatment type, landscape characteristics, site conditions, and mean observed or forecasted climate. For current treatments, we will use the outcomes of the FVS modeling in Objective 2 to predict treatment longevity based on key climate and ecological attributes that can be scaled to larger spatial scales using remote sensing data. Future projections of changes to treatment longevity will be determined by using FVS model runs of current treatment changes over time as baselines, and then running forecast models of fuels accumulation and vegetation change using the Climate-FVS module. We will do a suite of model runs under different climate scenarios to produce estimates of changes to treatment longevity over time with associated confidence intervals. We have access to Google Earth Engine and the United States Department of Agriculture's supercomputers (SciNet, https://scinet.usda.gov/) which will give us the capacity to conduct thousands of model runs and scale up our model estimates to high resolution maps for the Southern Rocky Mountains ecoregion.

III. Project Duration and Timeline

Table 3. Project timeline

	Year 1: Sept 2023-Aug 2024				**Year 2: Sept 2024-Aug 2025**				**Year 3: Sept 2025-Aug 2026**			
task	**fall**	**winter**	**spring**	**summer**	**fall**	**winter**	**spring**	**summer**	**fall**	**winter**	**spring**	**summer**
Meet with stakeholders												
Field work												
1. Fuel accumulation modeling												
2. Fire behavior modeling												
3. Treatment longevity modeling												
writing												

IV. Project Compliance - NEPA and Other Clearances

Treatments that will be measured here are complete with the necessary NEPA and other permitting. As this will be a remeasurement, we currently hold permits for monitoring sites on public lands and will work with individual property owners for those remeasurements of sites on private land.

V. Research Linkage - Not Applicable

VI. Project Outcomes

This project will result in an unprecedented longitudinal dataset of pre- and post-treatment fuels and vegetation characteristics that will lead to improved understanding of how climate and landscape factors affect the longevity of fuels treatments across central and northern Colorado. In doing so, this project will also develop and test quantitative thresholds for treatment longevity based on fuels accumulation and vegetation development changes as a function of time since treatment, landscape characteristics, and climate variability in the intervening period. These outcomes will address secretarial needs of reducing the occurrence and impacts of catastrophic wildfires through improved wildfire science and development of decision support tools. More specifically, the benefits of these outcomes will be fourfold:

1. Operations agencies will have access to **improved understanding and decision support tools** of the longevity of past treatments, improving their ability to plan for re-treatments where needed.

2. Published **maps of treatment longevity** into the future will provide **guidance for treatments** currently in the planning phase or to be executed in the future.
3. The broader fire science and science ecology field will benefit from a **comprehensive analysis of a robust dataset of long term treatment effectiveness** and will fill a much needed knowledge gap for scientists and practitioners.
4. Establishment of a **long-term, publicly available dataset** of forest structure following treatment that has the potential to be added to in the future in the form of additional measurements (15 year, 20 year) or added sites.

VII. Deliverables

Table 3. deliverable, description, and delivery dates

Deliverable Type	Description	Delivery Dates
Final Report	Detailed report of project results with associated data	August 2025
Completed Project Overview	Concise version of final report	August 2025
Decision support tool	Input site characteristics and estimate retreatment frequency	August 2025
Field visit with stakeholders	Visit sites with stakeholders to educate public about thinning treatments, discuss and adapt project goals, get input on field measurements	Spring, Summer, Fall 2024, 2025
Stakeholder Meeting 1	Discuss project goals and approach, solicit feedback	Winter 2023
Stakeholder Meeting 2	Update stakeholders on progress, insights	Winter 2024
Stakeholder Meeting 3	Share results, identify questions for future research and stakeholder needs	Winter 2025

VIII. Other Products

Table 4. Deliverables, description, and delivery dates

Deliverable Type	Description	Delivery Dates
Refereed publication	Fire behavior thresholds that define treatment longevity	Fall 2024
Refereed publication	Project synthesis paper on fuels treatment longevity in Colorado	Spring 2025
Refereed publication	Forecasting fuels treatment longevity using climate scenarios	Summer 2025
Non-refereed publication	Technical summary of study findings for distribution to operations agencies and other stakeholders	Fall 2025
Field tour summary	Summary of site visit to locations that show different treatment longevities	Fall 2025
Photos and Videos	Photos and Videos of study site conditions over time	Fall 2025
Models and geospatial tools	Predictive models and maps of treatment longevity	Fall 2025

IX. Roles of Investigators and Associated Personnel

Table 5. Roles and responsibilities of associated personnel

Personnel	Role	Responsibility
Dave Barnard	PI	Project management, data analysis, writing
Adam Mahood	co-PI	Data analysis, writing, supervision, field data collection
Allison Rhea	co-PI	Fire behavior modeling, writing, data analysis
Scott Ritter	co-PI	Fire behavior + fuels modeling, writing, data analysis
Camille Stevens-Rumann	co-PI	Writing, analysis, supervision
CFRI Data Analyst	Collaborator	Data management
Field Technicians	Field Technicians	Field data collection