MONITORING HANDBOOK

FOR EVALUATING FOREST MANAGEMENT OUTCOMES

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Document Development Statement: The purpose of this handbook is to provide guidance for the development and implementation of forest monitoring plans. Field monitoring and supporting adaptive management has been an integral part of the Colorado Forest Restoration Institute (CFRI) since its inception in 2005, and this handbook incorporates recommendations from the experience gained over the years. By describing the monitoring process, from developing monitoring questions to deciding on protocols and data management procedures, CFRI hopes to empower people to track management outcomes and long-term changes in forested environments. The goal of this handbook is to equip forest managers, field staff, and interested affected entities with the tools to develop an effective forest monitoring plan and establish standardized methods to create more opportunities for analysis and peer learning.

CFRI summary: The Colorado Forest Restoration Institute (CFRI) was established in 2005 as an application-oriented, science-based outreach and engagement organization hosted at Colorado State University (CSU). 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 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. We strive to earn trust through being rigorous and objective in integrating currently available scientific information into decision-making through collaborative partnerships involving researchers, land managers, policy makers, interested and affected stakeholders, and communities. CFRI holds itself to high standards of scientific accuracy and aims to promote transparency in the production and communication of science-based information. Always carefully evaluate sources for rigor and appropriateness before applying in your own work.

Acknowledgments: The authors would like to thank CFRI leadership for pioneering CFRI's monitoring program and the many employees that advanced CFRI monitoring, especially Tony Cheng, Brett Wolk, Camille Stevens-Rumann, Marin Chambers, Jeff Cannon, Emma Williams, Rob Addington, and Kristen Pelz. Thank you to Hannah Brown, Savannah Lehnert, and Camille Stevens-Rumann for thoughtful document review, Angela Hollingsworth for document layout and publication, and Maddie Wilson and Brooke Simmons for producing the monitoring handbook video series. Thank you to Chad Hoffman, Wade Tinkham, Mike Battaglia, and Paula Fornwalt for methods and analysis advice. Thanks to the more than one hundred Colorado State University students and the dozens of crew leaders that have made CFRI monitoring possible. Lastly, thank you to the many resource managers and affected entities who engage with CFRI; we appreciate the time they take to answer questions, discuss forest management, and support our monitoring program. This project was funded by the Colorado Forest Restoration Institute through the Southwest Forest Health and Wildfire Prevention Act.

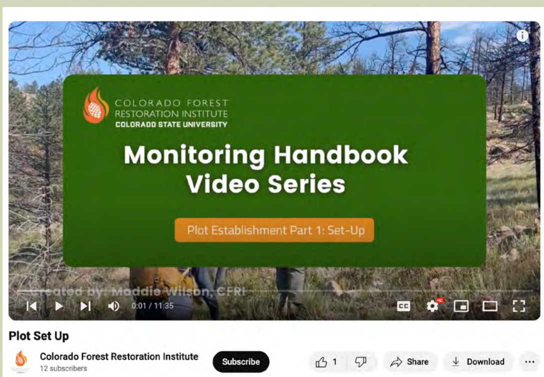
Publication Date: September 2024

Authors: Andrew Slack, Kat Morici, Kevin Barrett

Suggested Citation: Slack, A.W., Morici, K., Barrett, K.J. 2024. Colorado Forest Restoration Institute Monitoring Handbook for Evaluating Forest Management Outcomes. CFRI-2417.

HOW TO USE THE HANDBOOK

The Colorado Forest Restoration Institute Monitoring Handbook (the handbook hereafter) is designed to be an interactive document that can be read sections at a time. The guidance provided in the handbook is intended to help readers make decisions about developing monitoring plans. Specific directions on forest measurements are referenced in the Monitoring Handbook Video Series and additional external resources. The table of contents is intended to help readers navigate the document to easily reference necessary information.



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INTRODUCTION

Purpose of Handbook

This handbook provides a framework for monitoring the outcomes of forest management activities in conifer forests of the western United States using field-based data collection methods. Intended users include foresters, field technicians, and those working with forest management organizations to develop a plan for monitoring. The monitoring handbook is designed to help managers customize protocols for monitoring individual forest management projects, while promoting standard methods for data collection, sharing, and management. When data collected from multiple groups is similar, it can be used for larger, cross-organizational analyses of the outcomes of forest management across various spatial and temporal scales. For many forest management organizations, only minor changes to field data collection and management methods would standardize monitoring programs between partners, rendering data more compatible.

However, monitoring requires increased time and investment into individual projects, and many forest management organizations struggle to find the capacity and resources to support a robust monitoring program. Therefore, it is important to create efficiency by understanding what data is necessary, how much data to collect, and which projects provide the best opportunities to answer critical monitoring questions. Forest management organizations have different capacities for monitoring, and there are tradeoffs when making decisions about monitoring questions and methods.

The handbook discusses the importance and value of ecological monitoring before providing guidance on crafting useful and quantifiable monitoring questions. Next is a menu of metrics that may be used to answer monitoring questions. Finally, sampling design and methods used to collect data for each metric are described. Protocols are based on common forest inventory methods for measuring overstory trees. Additional protocols for measuring tree regeneration, canopy cover, surface fuels, understory plants, and ground cover can be added as desired. The Colorado Forest Restoration Institute (CFRI) uses these protocols to monitor the outcomes of silvicultural treatments, prescribed fires, and wildfires. Management actions that target the forest understory such as slash management (e.g. pile burning and mastication) or invasive weed management may also be monitored using these protocols with a greater emphasis on surface fuels and understory methods.

Photo credit: Andrew Slack, Hayman Fire 2021

Why Monitoring is Important

Addressing Uncertainty. Forest management actions can have a variety of impacts on long-term forest development. Furthermore, changes in land use over the last century (e.g. fire suppression and timber harvesting), a rapid expansion of human development in the wildland-urban interface, and climate change compound the amount of uncertainty foresters face when making management decisions. Uncertainty creates challenges to addressing management concerns such as increasing wildfire activity (US Forest Service 2022). However, collecting data before and after intentional and proactive forest management can provide the scientific information necessary to begin to collectively address uncertainty. Revisiting projects under a well-developed monitoring plan provides data to understand outcomes and develop science-based and locally relevant information to improve future management.

Foundation for Adaptive Management. Following a formal adaptive management process is a widely accepted approach to overcoming the challenges, uncertainty, and complexity associated with forest management. Adaptive management is an iterative process: a continuous cycle of planning, implementation, monitoring, and evaluation, in which managers are encouraged to experiment, collect data on actions, and use the results from the data to evaluate outcomes, learn, and adapt (DeLuca et al. 2010, Aplet et al. 2014). Collecting high-quality monitoring data is foundational to this process as it provides the scientific information to effectively facilitate the process of learning and adapting. Furthermore, data collected on local forest management projects provides locally relevant information and actionable knowledge, and avoids reliance on established scientific studies conducted in other landscapes or regions.

Supporting Collaborative Processes. Since forest ecosystems and processes occur across large areas, forest management also benefits from cross-boundary partnerships at landscape scales. This collaboration introduces another set of challenges associated with differing social and economic values and political conflict (Cheng et al. 2014). Monitoring helps facilitate collaborative processes by providing 1) specific information to help communicate and define ambiguous concepts and terminology; 2) a collective effort to help sustain collaboration and active participation; 3) peer learning opportunities to build consensus around future management decisions. Additionally, multi-party monitoring programs reduce the capacity burden of data collection and analysis and share the high investment into sustaining an effective monitoring program.

Monitoring at Different Scales

Forest management and collaboration occur at different spatial and temporal scales, and so should monitoring. It is important to understand how individual projects fit into larger forest management efforts. This handbook focuses on monitoring at the project-scale, but monitoring efforts accumulate over time, opportunities may emerge for larger analyses. Insights from a network of projects can be used to evaluate the impacts of adaptive management, forestry program outcomes over time, and cumulative impacts across a landscape (e.g. watershed).

Combining data from multiple projects and programs necessitates a common set of monitoring protocols across organizations. While any individual organization may not pursue program and landscape-scale monitoring, standardized data may still be shared among partners and made available to larger studies that inform broad trends in forest ecosystems and management.

Planning management activities and monitoring across scales can be challenging; consider using resources such as Aplet et al. 2014, Hessburg at al. 2015, and RMRS-GTR-365 (Tinkham et al. 2017). In particular, the U.S. Forest Service General Technical Reports RMRS-GTR-310 (Reynolds et al. 2013) and RMRS-GTR-373 (Addington et al. 2018) provide frameworks for defining and planning across spatial and temporal scales. These scales include:

Project

Project-scale monitoring provides information about a single forest management project (Figure 1). Typically, data is collected before and after a management action to assess whether the project achieved intended outcomes. Results may include changes in stand structure and composition, fuel loading, understory species, and modeled fire behavior. Maintaining plots in the long term over numerous data collection visits provides valuable information about forest management, such as sustained impacts and interactions with subsequent events (e.g. wildfire, drought, second entry management, etc.). In contrast, forest inventory plots are measured to capture immediate stand conditions and create a one-time snapshot of forest structure and composition within an area. A forest inventory is often used to determine specific management actions during project planning but does not provide data to understand project outcomes.

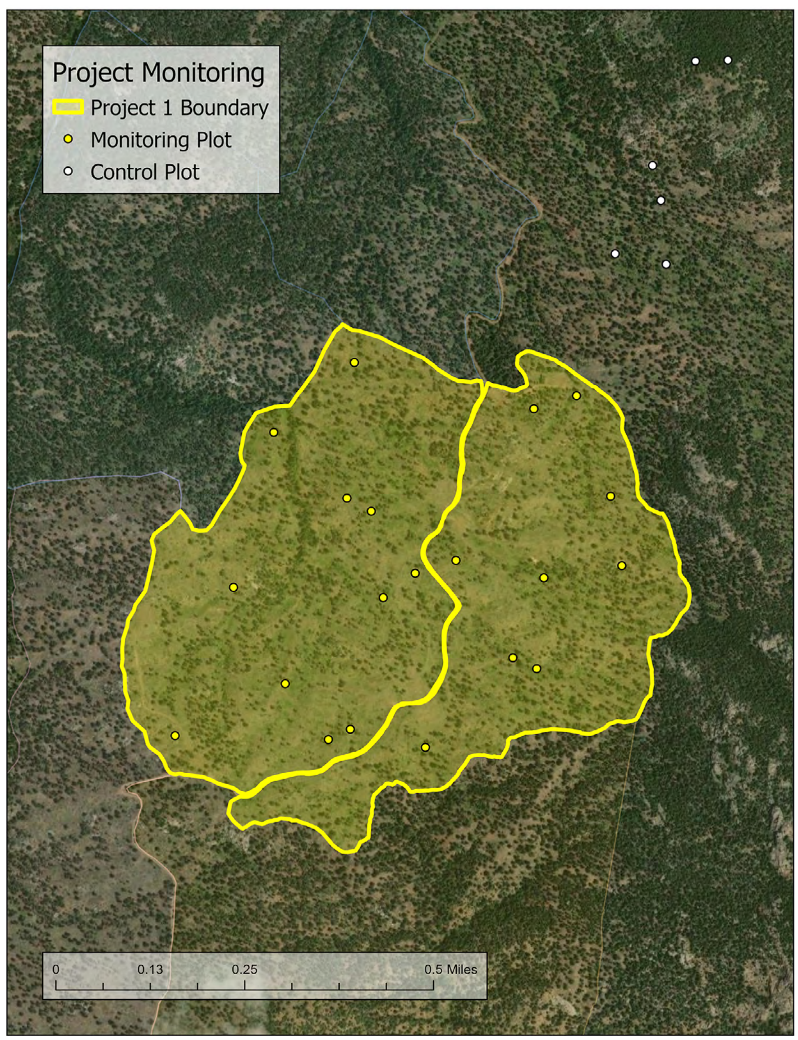


Figure 1. Map of established monitoring plots at a single project. Control plots are established outside of the project area.

Program

Program-scale monitoring compiles many projects within an organization, collaborative group, or funding source (Figure 2). Tracking the outcomes of many projects under a cohesive program can demonstrate the impacts of collaborative adaptive management, illuminate management activities that are more likely to result in desired conditions, and track program outcomes over time, see [Barrett et al. 2021] for an example of program monitoring.

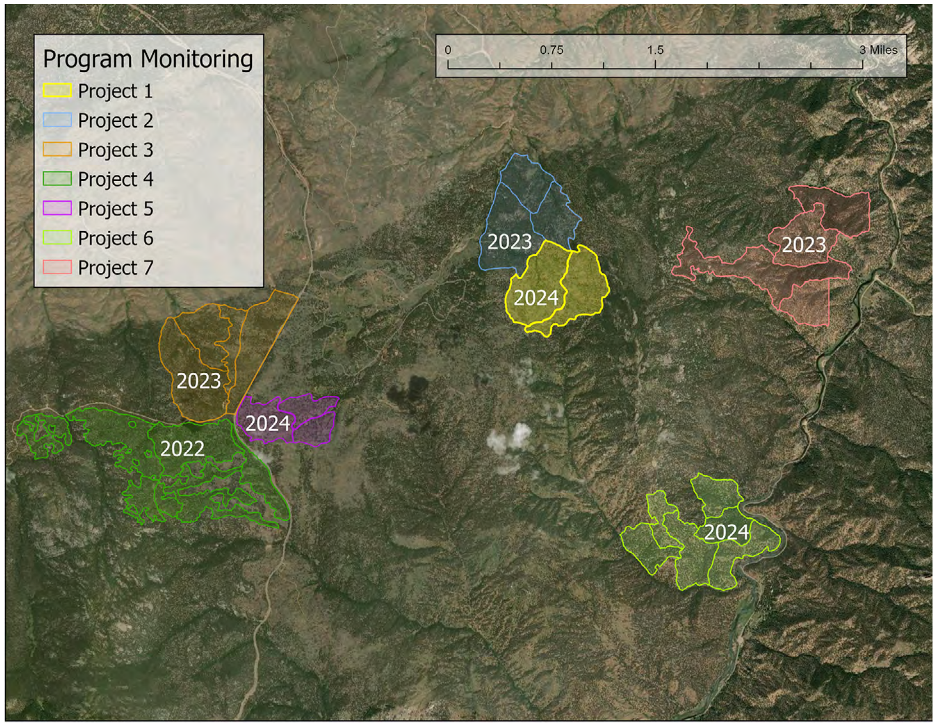


Figure 2. Map of multiple projects contributing to program monitoring. In this scenario, multiple projects from partner organizations contribute towards evaluating program level goals established by a local collaborative group.

Landscape

Landscape-scale monitoring compiles many projects to analyze the cumulative effects of forest management across a landscape (Figure 3). Forest management outcomes may also include analysis of untreated areas to evaluate progress towards landscape-level goals (e.g. Did the percent of the area predicted to support crown fire under severe fire weather conditions change within the watershed over the last 10 years?).

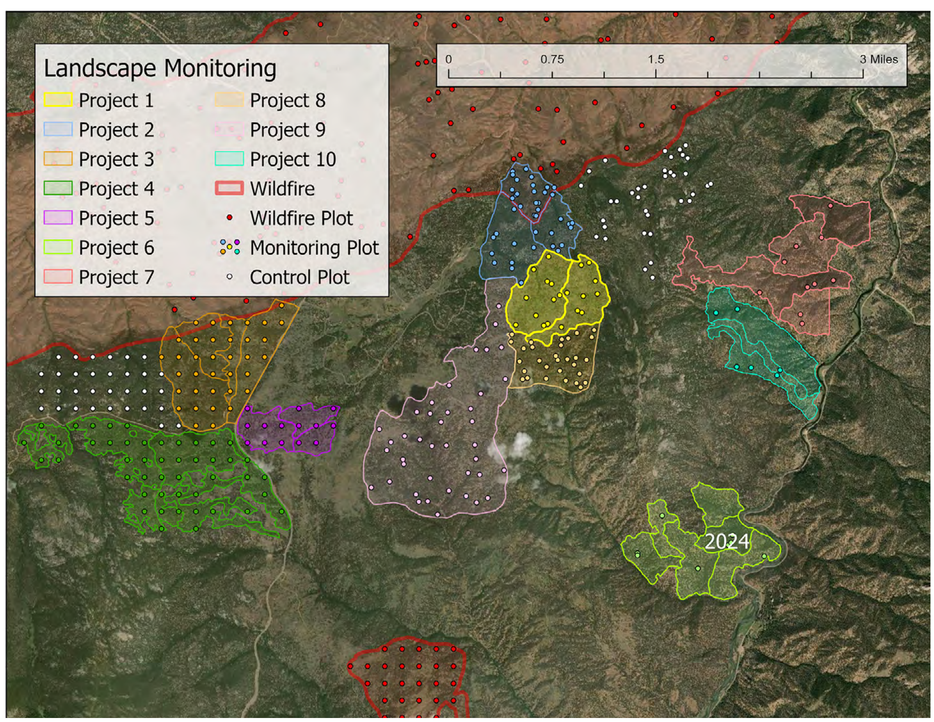


Figure 3. Map of a network of monitoring plots within forest management projects, wildfires, and unmanaged control sites. Cumulatively, these plots contribute towards evaluating forest change at a landscape scale.

IDENTIFYING MONITORING QUESTIONS AND METRICS

Developing Monitoring Questions

Monitoring questions are developed to track specific forest management outcomes or address scientific uncertainty. Monitoring metrics are the types of data collected that will be used to quantify outcomes. The purpose and need for monitoring will vary between projects and programs, for this reason the development of monitoring questions and metrics should be directly tied to the values, resources, and ecosystem services communities depend on forests to provide. Questions should additionally be tied to clear goals and objectives for management activities and appropriate metrics chosen to assess whether management activities have met the goals. Articulating desired conditions for the project site can in turn support the development of monitoring questions. Desired conditions describe characteristics of forest structure, composition, and condition identified as the target outcome for a site (Aplet et al. 2014); all of these characteristics can be assessed through various metrics to evaluate progress and address monitoring questions.

Often, monitoring takes place within a collaborative adaptive management context. Because collaboration brings together a diverse set of interests striving to build consensus around management decisions, it is important to avoid ambiguous terminology, provide clear definitions, and develop monitoring questions and metrics that are specific and measurable (Figure 4). Nuanced and iterative conversations between parties to establish shared understanding of terminology, management goals and objectives, and monitoring questions support the collaborative process and communication efforts to both internal and external audiences. Additionally, because time and money often constrain monitoring efforts, collectively prioritizing the most important monitoring questions can help streamline data collection.

1) Identify broader goals: Organizational goals, funder goals, landowner goals, collaborative goals

Goal: Reduce wildfire risk   Did the project reduce wildfire risk?

2) Add nuance: define ambiguous terms by tying them to important values, describe management activity

QUESTION: Did **mechanical thinning** reduce **wildfire hazard and predicted wildfire intensity near homes and other buildings**?

3) Make it measurable: include metrics and develop project objectives or targets

QUESTION: Did the mechanical thinning reduce wildfire hazard and predicted wildfire intensity near homes and other buildings? As measured by:

- **Limiting increases in fine woody fuel loading**
- **Reducing the number of plots that predict crown fire activity to less than 5 (out of 40 total plots)**
- **Lowering predicted total flame length to less than 10 feet**

Figure 4. An example of adding detail to a monitoring question so it defines ambiguous terms and is measurable.

Table 1: Multiple examples of identifying a broad monitoring question, improving the detail in the question, and making the question measurable. Monitoring questions are tied to desired conditions (DC) and project goals and objectives (G&O), and each of these statements should follow a similar process of adding detail. In each question, management activities are described in red, ambiguous terms are defined in yellow, and quantifiable metrics are added in green.

QUESTIONS THAT NEED IMPROVEMENT	MORE SPECIFIC QUESTION, BUT STILL NEEDS IMPROVEMENT	SPECIFIC AND MEASURABLE MONITORING QUESTION
Does the **project** reduce **wildfire risk**? DC: *Low wildfire risk* G&O: *Reduce wildfire risk*	Does **mechanical thinning** reduce the **potential for active crown fire behavior near evacuation routes**? *DC: Forest conditions that mitigate risk to life safety by supporting low fire intensity near evacuation routes.* *G&O: Reduce the risk of high intensity fire behavior near evacuation routes.*	Does **mechanical thinning** reduce the **potential for active crown fire behavior near evacuation routes** as defined by **the predicted total flame length and the number of plots that predict crown fire under severe fire conditions**? *DC: Forest conditions that mitigate risk to life safety by supporting low fire intensity near evacuation routes. Fire modeling predicts total flame length less than 5 feet and most plots (> 50%) to be surface fire type under severe fire conditions.* *G&O: Reduce predicted total flame length from 12 feet to below 5 feet. Reduce the number of plots predicting crown fire from 10 to less than 5.*
Does the **project** result in a **healthier forest**? *DC: A healthy forest* *G&O: Create a healthy forest*	Does **broadcast burning** promote a **desired understory plant community**? *DC: A healthy understory plant community that is maintained by prescribed fire.* *G&O: Promote native plants while preventing spread of non-native plants in the understory.*	Does **broadcast burning** promote a **desired understory plant community** by increasing **native species richness** and avoid significant increases in **non-native plant cover**? *DC: A healthy understory plant community as defined by native plant species richness and low cover of non-native plants.* *G&O: Increase the number of native plant species by 10% and limit non-native plant cover to less than 5% five years following implementation.*
Does the **project** improve **forest resiliency**? *DC: A resilient forest* *G&O: Create a resilient forest*	Does **hand thinning** improve **forest resiliency to bark beetle mortality**? *DC: Forests are resilient to bark beetle caused tree mortality.* *G&O: Promote forest conditions that are more resilient to bark beetles.*	Does **hand thinning** improve **forest resilience to bark beetle mortality** by **lowering tree density, promoting age diversity, and reducing bark beetle caused tree mortality**? *DC: Forests that maintain age diversity, have lower tree density and lower bark beetle caused tree mortality.* *G&O: Increase tree spacing by reducing tree per acre to less than 50, while maintaining age diversity where each size class is represented.*

Important Metrics and Terminology

Below are metrics that are commonly collected or calculated for forest monitoring and adaptive management. Metrics are divided into two categories: 1) forest structure and composition, 2) surface fuels and understory, and 3) modeled metrics—specifically fire behavior and effects. Depending on monitoring questions or areas of uncertainty, different metrics may be selected for inclusion in a monitoring plan. Each metric can be tracked before and after treatment to inform specific management outcomes. This list is not exhaustive but matches the data collection methods described in the data colleciton section. Additional metrics to address monitoring questions related to tree growth, soil stability, watershed health, wildlife habitat, etc. are not described here.

Table 2. Forest structure and composition metrics calculated with field data.

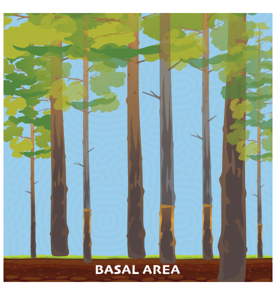
FOREST STRUCTURE AND COMPOSITION

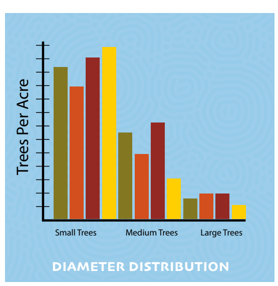
METRIC	MEASUREMENT METHOD	ECOLOGICAL OUTCOME
Basal area	Tree count with a prism or diameter at breast height (DBH) measurements of all trees within a fixed radius plot.	Cross-sectional area of trees at breast height for a given area.
Trees per acre	Diameter measurements with a prism or tree count within fixed radius plot.	Tree density; number of trees in a given area.
Tree species	Include species counts when measuring trees.	Tree species diversity and ability to separate tree metrics by species.
Quadratic mean diameter (QMD)	Diameter measurements with a prism or tree count within fixed radius plot.	A measure of average tree size, giving more weight to larger trees (there are different ways to calculate this).
Diameter distribution	Diameter measurements with a prism or tree count within fixed radius plot.	Graphical display of the number of trees by diameter size class.
Seedlings/ saplings per acre	Count the number of tree seedlings and saplings within a fixed radius plot.	Tree regeneration density.
Crown base height (CBH)	Height from the ground to the base of the lowest continuous green leaves/needles.	CBH, height, and DBH can be used to estimate canopy bulk density. CBH also impacts crown fire initiation.
Tree height	Height from the ground to the top of a tree.	Combine with CBH to calculate crown ratio. Also used for biomass estimates and combining with tree age to estimate site index.
Canopy cover	Count canopy hits vs openings.	Percent of an area covered by tree canopy.
Canopy bulk density	Calculated with tree DBH, height, and CBH.	The mass of available canopy fuel per canopy volume; aids in the prediction of crown fire spread.
Snags/Tree status	Record tree status (dead/ live) or stage of decay.	Separate tree metrics by dead and live trees.

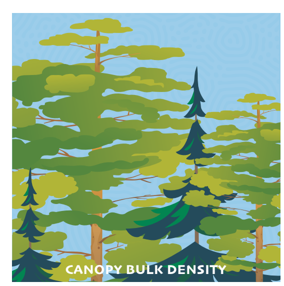
SURFACE FUELS AND UNDERSTORY

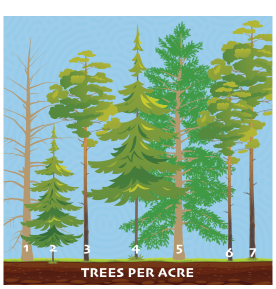
Table 3. Surface fuels and understory metrics calculated with field data.

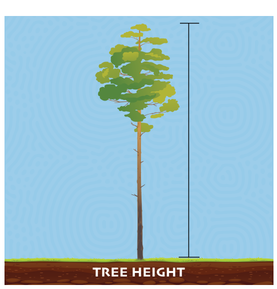
METRIC	MEASUREMENT METHOD	ECOLOGICAL OUTCOME
Fine woody fuel loading	Planar intercept (Brown's) transects or photoload estimation technique.	Weight of dead and down wood less than 3 inches in diameter for a given area.
Coarse woody fuel loading, decay status	Brown's transects or fixed area plots.	Weight of dead and down wood 3+ inches in diameter for a given area, may be separated by decay status.
Understory plant species of interest	Ocular estimate of plant species of interest within quadrats or line-point intercept technique along transects and/or presence within a fixed area plot.	Percent cover of the species of interest or presence/absence.
Understory vegetation growth form	Ocular estimate within quadrats or line-point intercept technique along transects.	Percent cover by growth form (graminoid, forb, shrub, tree).
Native, non-native, and noxious plants	Line-point intercept technique identifying all species along transects and/or identifying all species within a fixed area plot.	Percent cover or presence/absence of native, non-native, and noxious plants.
Plant species richness	Identify all species within a fixed area plot.	The number of plant species within an area.
Substrate	Ocular estimates within quadrats or line-point intercept technique along transects.	Percent cover of the forest floor by category: litter, duff, rock, soil, gravel, moss, lichen, coarse woody fuel, woody basal, and herbaceous basal material.

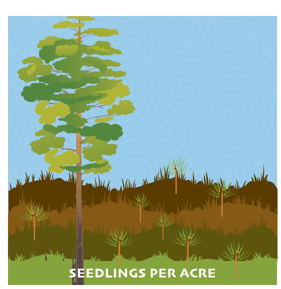


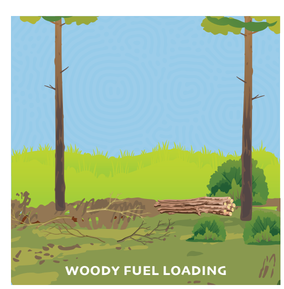












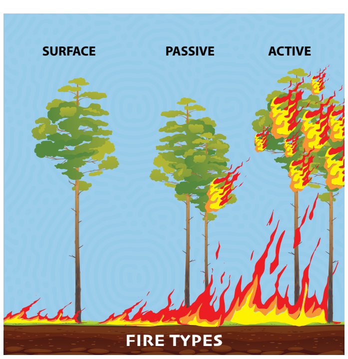
Modeled metrics Fire type, flame length, and tree mortality may be calculated under moderate and severe fire weather and fuel moisture conditions. The Fire and Fuels Extension of the Forest Vegetation Simulation (FFE-FVS) (Rebain et al. 2022), is a widely used application to produce these modeled metrics.

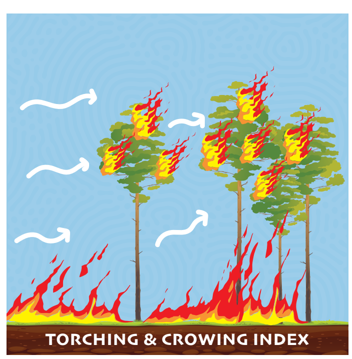
Table 4. Modeled fire behavior metrics produced by FFE-FVS.

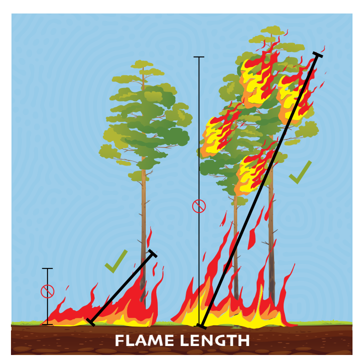
MODELED FIRE BEHAVIOR

METRIC	CALCULATION METHOD*	OUTCOME
Fire type	Fire modeling program output; inputs include fire weather, tree records, woody fuels, and fuel model.	Surface, passive, active, or conditional crown fire.
Flame length	Fire modeling program output; inputs include fire weather, fuel moisture, tree records, woody fuels, fuel model, and slope steepness.	Distance from the flame tip to the midpoint of the base of the flame.
Torching index	Fire modeling program output; inputs include surface fuels, fuel moisture, tree canopy base height, slope steepness, and wind reduction by the canopy.	The windspeed required to initiate crown fire activity (individual or group tree torching).
Crowning index	Fire modeling program output; inputs include fuel moisture, tree species, tree density, and slope steepness.	The windspeed required to sustain active crown fire.
Tree mortality	Fire modeling program output; inputs include fire weather, tree records, woody fuels, and fuel model.	Percent of the trees predicted to be killed by fire.
Probability of torching (P-Torch)	FFE-FVS program output; inputs include fire weather, surface fuels, fuel moisture, tree density, tree height, and slope steepness.	Probability of torching occurring within a small area of the stand. Calculated differently than torching index.

*Model inputs may change with advances in fire modeling







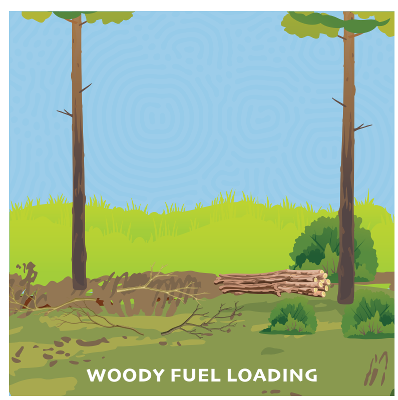
Valuable Metrics that are Frequently Forgotten

Several metrics listed above are frequently left out of inventory and monitoring plans. Here we describe these metrics in more detail, including what is captured and why this information may be of interest.

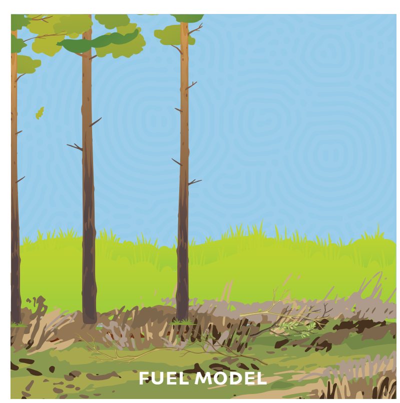
Canopy cover is the layer of branches and tree crowns that form above the forest floor and is measured as a proportion or percent of a fixed area that is covered by tree canopy. Canopy cover is a relatively easy metric to obtain and provides an indicator for a wide range of ecosystem services, and therefore is an important metric foresters use to describe forest conditions, define project goals, and capture horizontal heterogeneity. This metric can help managers identify and define vegetation patches, openings, tree density, and wildlife habitat. The forest canopy regulates the amount light reaching the forest floor and can influence local environmental conditions, understory plant communities, tree regeneration, and fire behavior. There are several ways to measure canopy cover in the field and using remotely sensed information such as aerial imagery.

Crown base height (CBH) is the distance from the forest floor to the lowest continuous live tree branches. CBH is important because it influences how easily a fire propagates from the ground into the crowns of trees. CBH and tree height are valuable metrics to collect in order to accurately model fire behavior and tree mortality.

Fine woody fuels are dead and down woody fuels less than 3 inches in diameter. They influence fire spread and fireline intensity, thus are useful to collect when surface fuels and fire behavior are a management concern. Thinning treatments without additional surface fuel management activities typically increase fine woody fuel loading and therefore increase fire behavior (Fulé et al. 2012). Tracking the amount and duration of changes in fine woody fuels can help inform the feasibility of reintroducing fire.



Fuel models are a set of fuelbed inputs used to predict fire behavior. Fuel models are not a traditional forestry metric but choosing an appropriate fuel model improves fire behavior predictions such as rate of spread and flame length. Custom fuel models may be built with detailed information about surface fuel loading, surface area to volume ratios, moisture of extinction, and heat content. However, it is more common to assign a predefined fuel model to each field plot using either the 13 original fuel models (Anderson 1982) or the 40 Scott and Burgan fuel models (Scott and Burgan 2005). Selecting a fuel model is important when predicting fire behavior because the most appropriate fuel model can be selected to match on-the-ground conditions. This results in a higher likelihood of predicted fire behavior matching actual fire behavior. FVS assigns a fuel model based on the tree list if one is not provided, however the automatically selected model may not be a good match for field conditions. Assigning a fuel model in the field is a quick and easy way to improve fire behavior predictions.



DATA COLLECTION

Sampling Design

Sampling Intensity

Sampling intensity is an important consideration when designing a monitoring plan because it influences the precision (or accurate representation) of the results. The following guidelines can help determine an appropriate number of plots for monitoring projects. Larger sample sizes yield more precise results and may be necessary to adequately capture a metric of interest when forest conditions are highly variable within the monitored area. For example, surface fuels are often variably distributed within a plot and across plots, especially after mechanical treatments, so more sampling points and/or plots will give a better picture of the conditions. Plot density should be proportional to the amount of variability observed in pre-treatment forest conditions and expected from the treatment (Figure 5). The size of the project can also influence sampling intensity. In general, the number of acres per plot is higher on larger projects. For example, US Forest Service projects tend to be larger and on average CFRI installs one plot for every 12 acres on federal land, where projects on non-federal land (e.g. state, county, private) are often smaller and have one plot for every 4 acres. On average CFRI installs one monitoring plot for every 8 acres across all projects, and this results in approximately 5-40 plots established on projects ranging from roughly 5-1000 acres. However, CFRI recommends a minimum plot count of 5 on the smallest of projects, and installing as many plots as capacity allows on the largest projects.

A power analysis may be used when designing monitoring studies intended for scientific publication to calculate the smallest sample size needed for results that are truly significant and not by chance. However, this is likely not necessary for most monitoring plans that strive to produce locally relevant information to facilitate peer-learning and adaptive management. Given resource constraints, CFRI recommends performing a power analysis only when capacity allows and the data will be included in statistical analyses.

Figure 5. When determining sampling intensity, consider heterogeneity that may be created by the project. In this photo of a prescribed fire unit, the area circled in red burned at high severity and an unburned area is circled in white.

Stratification

When an area contains multiple forest conditions or different management actions are planned within a larger area, consider stratifying the sampling area into subunits where like forest types and treatment types are grouped together. For example, forest conditions and treatment intensity may differ for an area that previously experienced a wildfire within the boundaries of a project, thus it may be beneficial to delineate a subunit for the wildfire area and another subunit for the unburned area. Furthermore, different management actions such as thinning intensity or treatment methods (e.g. hand thinning vs. mechanical thinning) may necessitate further stratification of the project (Figure 6). A set number of plots can be installed within each subunit. Other stratification approaches include north/south aspect, riparian/upland areas, wet/dry topographic wetness index, and different forest types within the same project. Stratification of a sampling area ensures variability is adequately captured and allows for comparisons between different forest types or treatments.

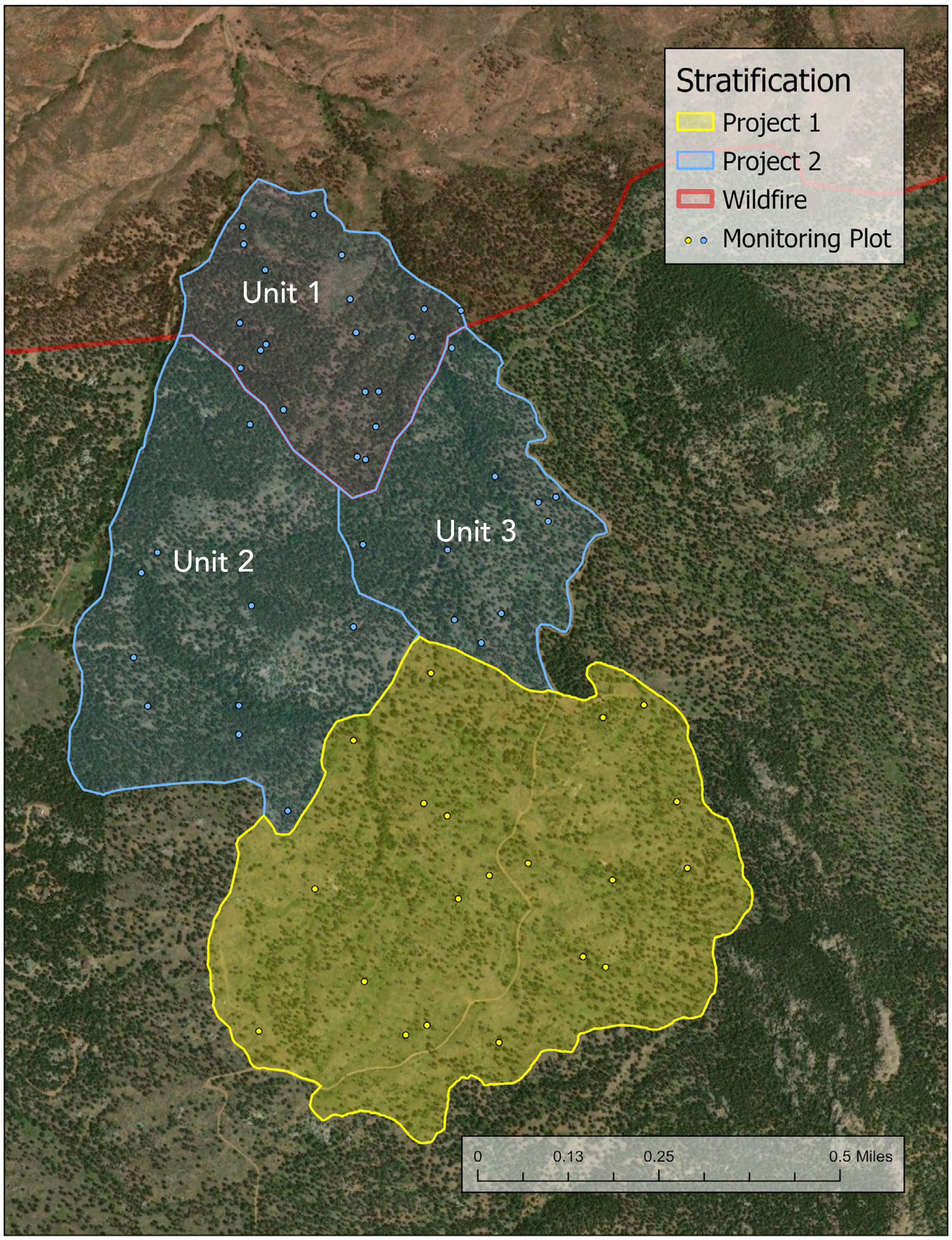


Figure 6. Map of two projects that highlight the need for stratification. The first project in yellow includes only one management unit because conditions and management actions are consistent throughout the project area. The second project in blue includes 3 treatment units where a wildfire burned through unit 1, and units 2 and 3 have different management actions.

Establishing Plots

Plot Placement

After determining sampling intensity, plots may be established using random placement or gridded across the area. When establishing a new plot, make sure that the GPS point falls in an area that is suitable (e.g. not on a road, project boundary, within 100’ of an existing plot, etc.). It is important to install permanent plot markers to aid in the re-location of monitoring plots.

PLOT ESTABLISHMENT PART 1: SET-UP

https://youtu.be/Eszg_4yfWtQ?si=q37GRqNt0-HPKduC

Random plot locations can be selected with geospatial software or in the field using a random number table to walk a random distance along a random azimuth between plots.

Benefit: Reduces bias, every part of the forest has an equal chance of being sampled.

Drawback: Note that randomly located plots may be clustered in one area of the unit and under-represent areas of interest within the project area (e.g. riparian zones).

If plots are located using random placement and a plot needs to be moved (e.g. located on road/trail), use a random number table/generator to choose a direction and distance to move the point to a suitable area.

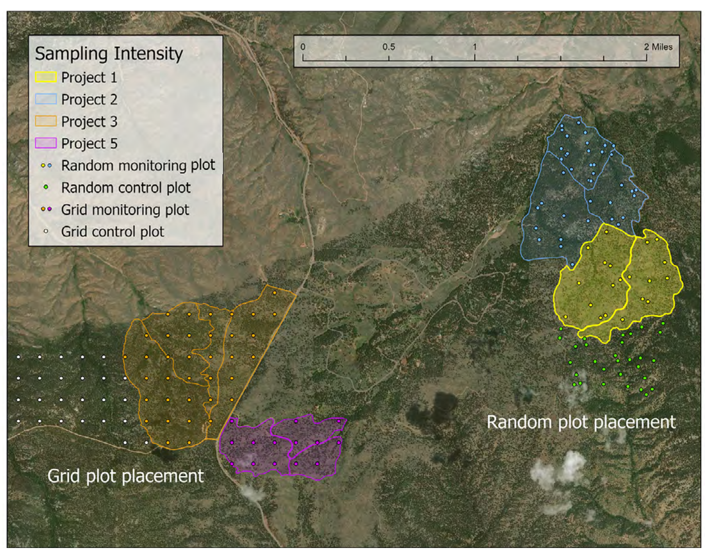
OR

Gridded plots can be located with geospatial software or in the field using a consistent bearing and distance between plots.

Benefit: Ensures uniform spatial coverage and easier to locate plots.

Drawback: Less adaptable to irregular or complex terrain, and may require more plots to capture variability.

If plots are gridded, consider skipping plots that are not in appropriate areas.



Helpful hints for relocating a plot:

- Use a georeferenced map or GPS coordinates.
- Use a metal detector if plots were marked with a metal stake.
- Match the plot location using previous plot photos. Look for distinctive rocks, branches, snags, topography, etc.

Naming Convention

Each plot should be given a unique name that includes a unit identifier and plot number. If monitoring is being implemented for a program or organization, establish a consistent naming structure that can be used across all projects and sites. For example, CFRI uses a three-letter site code followed by a unit identifier and a plot number [e.g. OPH-1T1-01]. Plot names should remain consistent and standardized over time.

A good naming convention is unique, includes a location identifier, and remains consistent over time.

Example: A plot within the Some Treatment project area located on a south slope in unit 1 could be called "STE-1S-01".

A bad naming convention is non-specific or inconsistent.

Example 1: "Plot 1" does not include any information about the project area or location and could be repeated at multiple sites.

Example 2: "STE-1S-01" is not the same as "STE-1S-1" or "STE-1S-001". Use a standard number of digits for plot numbers.

Photo credit: CFRI

Photo credit: CFRI

Photo credit: CFRI

The following sections provide guidance on selecting data collection methods, and describe benefits and drawbacks when multiple methods are presented. For detailed information about each method, refer to the Sample Data Collection Protocol in Appendix A or Additional Resources in Appendix B.

PLOT ESTABLISHMENT PART 2: INFORMATION

https://youtu.be/-qXg4gcUmvU?si=47unzHHXdubdp0kQ

Plot Information

Plot information is descriptive data that can be used to organize plots for database management and meta-analyses, perform spatial analyses, and help tell the story of forest management. The following information may be taken at each plot:

Plot Name	Record the unique plot name.
Coordinates	Plot location (GPS coordinates) and datum (usually WGS 84 or NAD 83). Set the GPS unit on the ground at plot center to collect coordinates.
Plot Notes	Record notes on plot location (e.g. near road, rocky outcrop, project boundary) or past disturbances (e.g. fire, insect outbreaks, animal signs/grazing, human disturbance, etc.).
Photos	Take a set of photos during every plot visit. Photos should be taken at an established location (usually plot center) with defined orientations (e.g. North, East, South, and West) and camera angles (e.g. canopy, eye-level, and ground). This creates consistency between plot visits so before and after photos are correctly aligned with each other.
Aspect	Using a declinated compass, measure the hillslope aspect in degrees (0-359) within the 1/10th acre plot. This is the direction a ball would roll down the hill, and should be collected facing downhill.
Slope	Using a clinometer, record the slope of the hillside along the aspect to the nearest percent within the 1/10th acre plot. Take slope measurements from plot center both downhill and uphill and record the average slope of the two measurements.
Elevation	Record elevation from GPS unit.
Fuel Model	Assign a fire behavior fuel model to the plot using either the 13 traditional fuel models or 40 Scott and Burgan fuel models. Refer to both written descriptions and photos to select an appropriate fuel model. Highly recommended for fire behavior modeling.

Example protocols that include descriptive plot information are located in Appendix A.


Pre thin and burn (2016)


Post thin and burn (2017)


1 year post thin and burn (2018)

Forest Structure and Composition

The following protocols are used to measure trees (overstory trees, tree regeneration, and canopy cover) in order to calculate metrics such as those described under forest structure and composition (Table 2). Additionally, forest structure and composition data can be combined with surface fuels and understory data to produce modeled fire behavior metrics (Table 4).

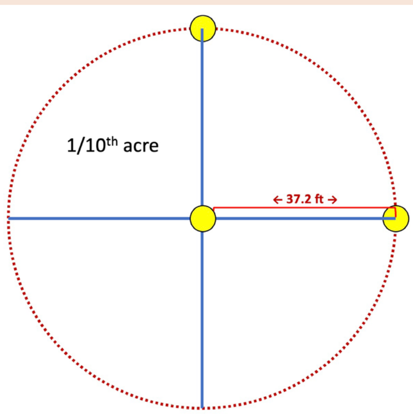
Overstory Trees

CFRI defines overstory trees as greater than or equal to 5 inches in diameter at breast height (DBH). The data collected from overstory trees can be used to calculate forest structure and composition metrics, including basal area, trees per acre, and species composition. Two methods are commonly used to measure overstory trees: fixed area and variable radius plots. In general, the decision to establish fixed area versus variable radius plots should balance the capacity and needs of the monitoring program. CFRI recommends establishing fixed area plots for monitoring, especially if there is interest to maintain long-term monitoring plots.

Fixed area plots involve measuring all trees within a fixed area. The size of the plot varies based on the tree density of an area, but should remain consistent for all plots within a unit. In dry forests, a circular 1/10th acre plot (37.2 ft radius) is common. In moist, denser forests, a smaller plot (e.g. 1/20th acre) may be used.

Benefit: Fixed area plots are better for comparisons to aerial imagery; clear plot boundaries help facilitate consistent measurements over multiple visits.

Drawback: Often more time-consuming than variable radius plots in dense areas, may be difficult to establish the plot boundary.



Fixed area plot example.

Example protocols that include descriptive plot information are located in Appendix A.

OR

Variable radius plots use a wedge prism to determine which trees are "in" the plot. It is important to select an appropriate Basal Area Factor (BAF) prism for the forest type, and for the BAF to remain consistent within a site over time. On the Front Range of Colorado, a 10 BAF prism is appropriate in most forest types. In dense lodgepole or spruce-fir, a 20 BAF prism may be preferable.

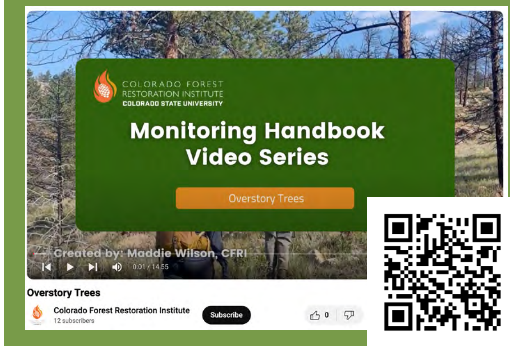
Benefit: Simple and fast data collection; gives a rapid estimate of basal area.

Drawback: Difficult to use in dense brush and easy to miss large trees that are far away or trees behind other trees; ambiguous plot boundary can lead to inconsistent measurements between visits.

Variable radius plots use a wedge prism to determine which trees are "in" the plot.

Example protocols for variable radius plots are found in the CFRI Simple Plot Protocol (Additional Resources, Appendix B)

OVERSTORY TREES



https://youtu.be/8Anat1DKO-8?si=lgh9F_qEkROM179t

The following data may be recorded for every tree:

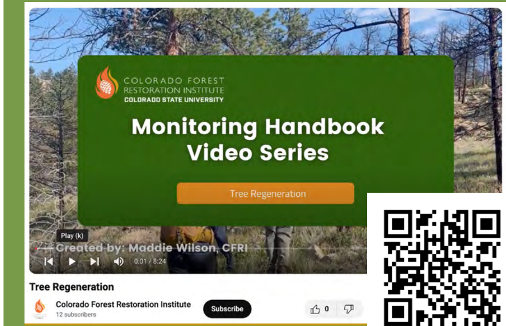
Species	Commonly recorded as 4-letter USDA plant code (e.g. ponderosa pine is PIPO).
Status (Live/Dead)	A tree is live if it has any green leaves or needles. Deciduous trees must be measured during the growing season.
Diameter at breast height (DBH)	Diameter of tree bole at a height of 4.5 feet from the ground. This is typically collected with a diameter tape or logger's tape.
Height	Distance from the ground to the top of the tree. This is often measured with a clinometer and logger's tape, hypsometer, or laser rangefinder.
Crown base height (CBH)	Distance from the ground to the lowest continuous needles/leaves for live trees.
Notes	Record unique information about the tree (e.g. leaning, dead top, etc.).

Photo credit: Andrew Slack

Tree Regeneration

Fixed area plots provide the best density estimates for small diameter trees and seedlings. Traditionally, a circular 1/100th acre plot (11.78 ft radius) is used to measure tree regeneration. However, tree regeneration is often patchy so increasing the size or number of plots gives a more accurate measure of seedlings and saplings.

TREE REGENERATION



https://youtu.be/8Anat1DKO-8?si=HC0MISCj5OO_CavG

Saplings

Saplings are young trees; the cutoff between saplings and overstory trees can be defined in various ways. CFRI defines saplings as trees at least 4.5 feet (ft) in height and less than 5 inches DBH. The same data recorded for trees may also be recorded for every sapling (see table above).

Seedlings

Seedlings are live trees less than 4.5 ft tall. The number of seedlings of each species are counted within a fixed area plot. Seedling tallies may be further divided into height classes. The following seedling data may be recorded:

Tally by species	Count the number of individual seedlings by species. Species is difficult to determine for recent germinants and they typically have low survival rates. Consider using a minimum height to exclude recent germinants or collecting germinants as a separate class.
Tally by height class	Seedlings may be divided into height classes (e.g. 4-12 inches, 12-32 inches, 32-53 inches).

Seedling

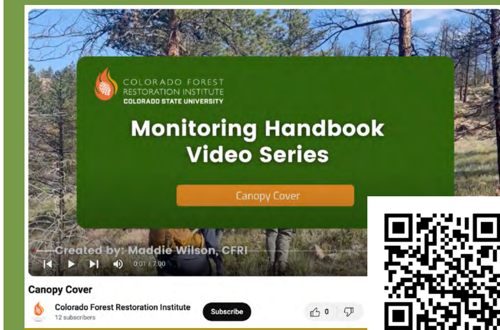
Germinant

Example protocols for measuring saplings and seedlings are found in Appendix A.

Canopy Cover

Canopy cover is the percentage of the ground that is covered by tree crowns and can be measured directly in the field or using a GIS program. This handbook is focused on presenting options for field-based methods; however, here options for measuring canopy cover in the field and in the office using a GIS program are provided.

CANOPY COVER



https://youtu.be/8Anat1DKO-8?si=MgUPoQ9C39atvch5

Field Methods

Benefit: Available to collect immediately following treatment. Field-based canopy cover measurements can provide more detailed information about overstory composition and are directly related to other field-based metrics such as regeneration and understory plant communities.

Drawback: Requires more field time and provides plot-level estimates that do not cover the entire project area.

A **point estimate** can be used to measure canopy cover at one or more established points within a monitoring plot. A densiometer is necessary for this method.

Benefit: A relatively quicker method for measuring canopy cover in the field.

Drawback: Only provides a single canopy cover estimate.

A densiometer.

Instructions for collecting point estimates of canopy cover using a densiometer are located here: https://www.forestry-suppliers.com/Documents/1450_msds.pdf.

OR

Line intercept methods can be used to record canopy cover along a transect. This uses a densitometer.

Benefit: Additional data can be recorded in categories such as canopy cover species composition and tree groups.

Drawback: Takes relatively more time in the field.

Using a densitometer along a transect.

Example protocols for collecting canopy cover using the line intercept method are found in the CFRI Simple Plot Protocol (Additional Resources, Appendix B).

GIS Methods

LANDFIRE data

LANDFIRE is a wildfire management program that provides landscape scale geospatial products. Download the Forest Canopy Cover (CC) layer under the Canopy Fuel data. The CC layer is a raster dataset that estimates canopy cover for each 30-meter pixel. In a GIS program, average the canopy cover values of each cell within the project area or unit to provide an estimate for canopy cover. This method works best for projects and management units greater than 100 acres, and only provides a rough estimate for canopy cover.

Random Point Method

In a GIS program, identify the areas within the project to provide an estimate for canopy cover. If forest conditions are homogenous across the project area, then one estimate for the entire project should suffice. However, if there is a lot of variability in canopy cover within the project area, consider stratifying the project boundary into smaller sampling units and estimate canopy cover for each unit.

To get a percent canopy cover estimate to the nearest 1% for your area of interest (e.g. project or management unit boundary) place a 100 randomly located points within the boundary. Using the aerial imagery basemap, zoom in as close as possible and determine whether each point overlays tree canopy (Figure 7). For each point mark a 1 for canopy and a 0 for no canopy. You can do this in GIS program, a separate sheet of paper, or excel sheet, but keep track of which points have been recorded. When all 100 points have been recorded, count the total number of points that recorded canopy. This total will be your first estimate for canopy cover.

Add an additional 50 random points within the boundary and record canopy or no canopy for each point as described above. Count the total number of points that recorded canopy for all 150 points and divide by 150. This gives you the second estimate for canopy cover. If the second estimate is not similar to the first estimate (more than ± 5%), add another 50 points to come up with a third estimate. Repeat these steps to add more points until the new estimate is close (within ± 5%) to the previous estimate. When there is no change between estimates for canopy cover record the final number.

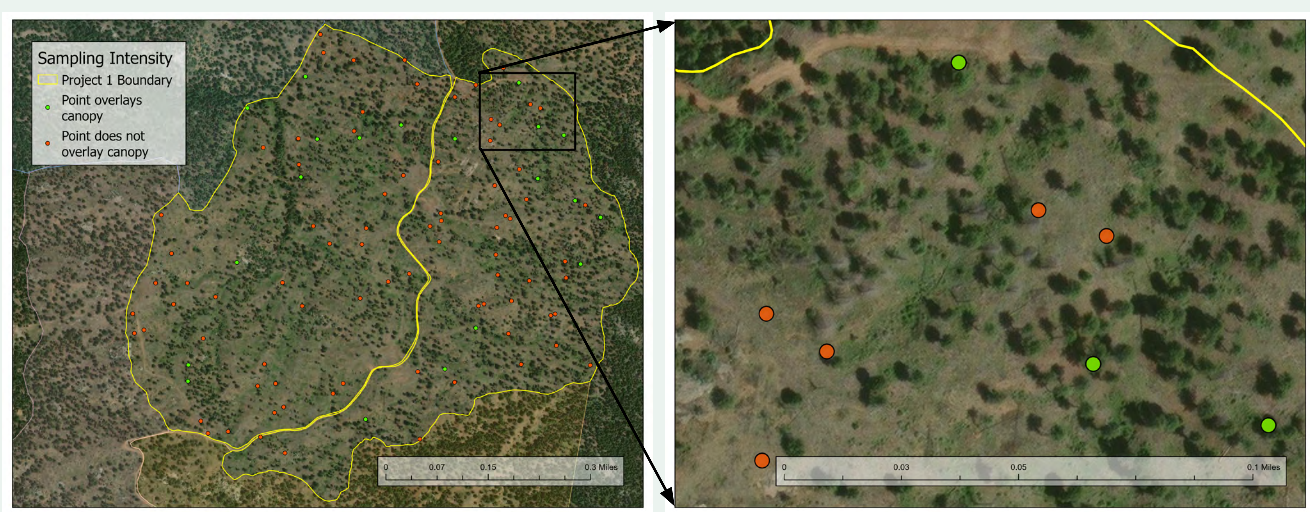
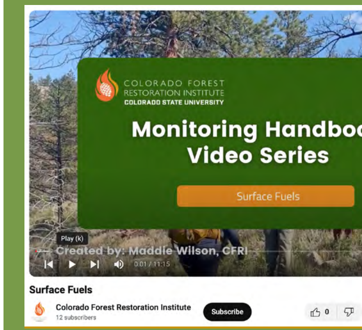


Figure 7. A map of estimating canopy cover using a GIS program. One hundred points are randomly placed within the project boundary. Zoom in to determine if each point overlays canopy (green), or no canopy (red). This example estimates canopy cover at 20%. More random points should be added to verify the accuracy of this estimate.

Surface Fuels and Understory

The following protocols are used to measure surface fuels and understory in order to calculate metrics in Table 3. Surface fuels are the dead woody debris, herbaceous vegetation, and shrubs that carry fire. They are often heterogeneously distributed, consequently a large sampling area and/or multiple subplots are required for accurate estimates.

SURFACE FUELS



https://youtu.be/KZjlREB1Kak?si=6hOhDb4tokHXFmzX

Fine woody fuels

Fine woody fuels are dead and down wood less than 3 inches diameter. A go-no-go gauge should be used to divide fuels into the following timelag size classes:

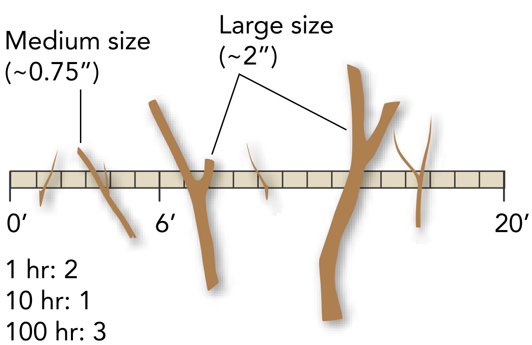
1-hour (0-0.25 inches in diameter)
10-hour (0.25 -1 inches in diameter)
100-hour (1-3 inches in diameter)

Two methods are commonly used to quantify fine woody fuel loading, or weight per unit area:

Planar intercept transects (Brown 1974) involve tallying the number of intersecting pieces of wood by size class. The number of transects per plot and transect length may vary based on surface fuel conditions but should remain consistent within a unit. Brown (1974) suggests measuring 1- and 10-hr fuels along 6 ft of the transect and 100-hr fuels along 12 ft, but longer transect are needed when fuels are sparse.

Benefit: Easy to train surveyors to tally fine fuels by size class.

Drawback: May need many transects to get an accurate estimate of fuel loading.



Planar intercept transect with 1- and 10-hr fuels tallied along 6 ft of the transect and 100-hr fuels tallied along 20 ft.

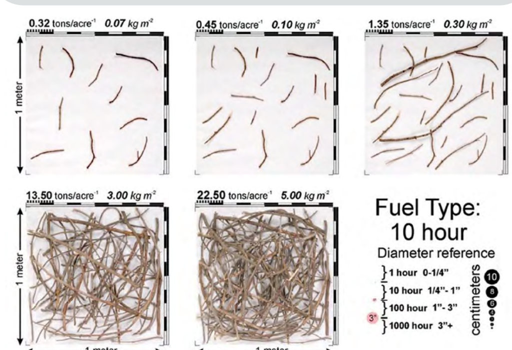
Instructions for using the planar intercept method are found in Brown (1974). (https://www.fs.usda.gov/rm/pubs_int/int_gtr016.pdf)

OR

Photoload sampling uses a series of photographs as a guide to visually estimate the amount of fuel in each size class within a 1 m² quadrat. Multiple quadrats per plot are recommended to account for variability in surface fuel conditions. Keane and Dickinson (2007) suggest a 10% subsample of the plot area, but acknowledge 1% is more feasible. A 1% subsample of a 1/10th acre plot is 4 quadrats.

Benefit: Trained surveyors may complete visual estimates rapidly.

Drawback: Calibration between surveyors is important for consistency, and calibration to known fuel weights is vital for accuracy.



Photoload sampling uses a series of photographs as a guide to visually estimate the amount of fuel in each size class within a 1 m² quadrat.

Example protocols for using the photoload method are found in the CFRI Simple Plot Protocol (Additional Resources, Appendix B).

When using the photoload method it is important to calibrate field observations of fine woody fuels, and if capacity does not allow for calibration CFRI recommends using the planar intercept method. Two calibration methods include: 1) Train crews prior to data collection in the field by adjusting crew member estimates to known amounts of each fuel size class and having crews practice. Consider collecting low, medium and high fuel loading for each size class and mixed size classes. 2) Build a calibration equation by destructively collecting numerous quadrats in the field, where crews estimate fuel loading before all fine woody fuels are collected, then samples are brought back to the lab, oven dried and weighed by size class. Both methods require destructive sampling of fine fuels in the field by collecting all fuels in a quadrat, measuring the actual dried weight, and having crews adjust their observations prior to data collection (option 1), or developing a calibration equation to adjust observations to the known weights of sampled quadrats (option 2). See Keane and Dickinson (2007) for more information about the first calibration method and Morici and Cannon (2019) for more information on the second method.

Photo credits: CFRI

Coarse woody fuels

Coarse woody fuels, or 1000-hour fuels, are dead and down wood 3 inches or greater in diameter. They are often divided into decay classes or classified as sound or rotten.

Two methods are commonly used to quantify coarse woody fuel loading:

Planar intercept transects (Brown 1974) involve measuring the diameter and decay status of intersecting pieces of coarse woody fuel along a 50 ft transect. The number of transects per plot may vary based on surface fuel conditions but should remain consistent within a unit.

Benefit: Easy to train surveyors.

Drawback: Less accurate plot-level estimate.

Measuring the diameter of a coarse woody fuel on a transect.

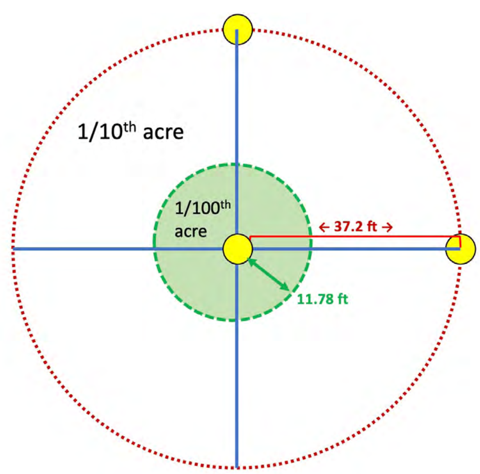
Instructions for using the planar intercept method are found in Brown (1974). (https://www.fs.usda.gov/rm/pubs_int/int_gtr016.pdf)

OR

Fixed area plots involve measuring decay status, two diameters, and a length for all pieces of coarse woody fuel within the plot. The plot size may vary depending on the arrangement of coarse woody fuel and desired accuracy but should remain consistent within a unit. A 1/10th acre plot may be used when fuel is sparsely distributed or higher accuracy is desired. A 1/100th acre plot may be used when coarse woody fuel loading is heavy or lower accuracy is acceptable.

Benefit: More accurate plot-level estimate.

Drawback: Time consuming in areas with heavy coarse woody debris.



Fixed radius plot example.

Example protocols for using fixed area plots for coarse woody fuels are found in the CFRI Simple Plot Protocol (Additional Resources, Appendix B).

Understory Plants

The understory includes plants growing beneath the forest canopy. Understory plants may be measured to the species level or grouped into life forms (graminoid, forb, shrub, tree). Additionally, species of interest may be identified, such as noxious weeds or plants important for wildlife habitat and forage. Grouping species to life form or only identifying species of interest reduces sampling time but yields a less complete picture of the understory plant community.

Percent cover by understory plants may be collected via the following two methods:

UNDERSTORY PLANTS

https://youtu.be/90RCKaPyjHs?si=NNzzZkzl1OcTzjO-

Visual estimation within a 1m² quadrat yields the approximate percent cover of each substrate. Multiple quadrats may be measured per plot.

Benefit: Rapid assessment of forest floor substrate.

Drawback: May be inaccurate, requires calibration between surveyors.

Estimating percent cover of understory species in a quadrat.

Example protocols for visually estimating understory plant cover in quadrats is found in the CFRI Simple Plot Protocol (Additional Resources, Additional Resources, Appendix B).

OR

Line-Point Intercept transects use a set number of "hits" along a transect to record every substrate encountered. Multiple transects may be measured per plot.

Benefit: Precise and repeatable.

Drawback: May be time-consuming.

Using a pin flag to record each species encountered at set points along a transect.

Example protocols for using the line-point intercept method for understory plants are found in the CFRI Mothership Protocol (Additional Resources, Appendix B).

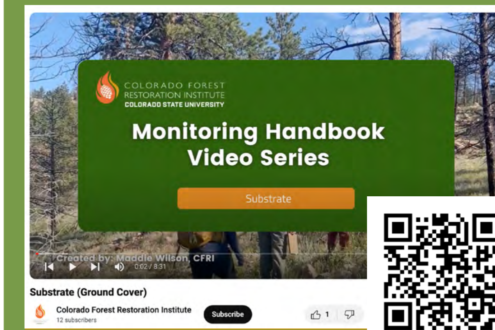
Plant species richness requires a complete species survey and is best measured within a fixed area plot by systematically searching for and recording all plant species present in the plot. An appropriate plot size depends on the heterogeneity of the understory plant community as well as desired accuracy.

Ground Cover (Substrate)

Substrate measurements provide information about growing space and conditions by categorizing the forest floor into the following classes:

- **Litter/Duff**: non-woody debris; includes detached dead herbaceous material, needles, bark, and pinecones
- **Bare Soil/Gravel**: mineral particles that are < 0.5 inches
- **Rock**: mineral particles ≥ 0.5 inches
- **1000-Hour Fuels**: woody fuels with a diameter ≥ 3 inches and NOT suspended from the ground
- **Moss/Lichen**: any moss or lichen that is growing on the ground; moss or lichen growing on a rock is counted as rock
- **Woody Basal**: large, rooted woody vegetation; primarily tree trunks, stumps, and roots
- **Herbaceous Vegetation Basal**: dense plant material that suppresses growing space for other plants; bunchgrasses

SUBSTRATE



https://youtu.be/7nuHHg2AbTQ?si=ObXxSCkdHFUfrucu

Substrate cover may be collected via the same two methods as understory plants:

Visual estimation within a 1m² quadrat yields the approximate percent cover of each species or life form. Multiple quadrats may be measured per plot.

Benefit: Rapid assessment of understory plant cover.

Drawback: Requires calibration between surveyors and may be too small of an area to accurately capture shrub cover.

Estimating percent cover of each substrate class within a quadrat.

Example protocols for visually estimating understory plant cover in quadrats is found in the CFRI Simple Plot Protocol (Additional Resources, Appendix B).

OR

Line-Point Intercept transects use a set number of "hits" along a transect to record every species or life form encountered. Multiple transects may be measured per plot.

Benefit: Precise and repeatable.

Drawback: May be time-consuming, especially in heavily vegetated areas.

Using a pin flag to record each substrate encountered at set points along a transect.

Example protocols for using the line-point intercept method for understory plants are found in the CFRI Mothership Protocol (Additional Resources, Appendix B).

Additional Considerations

Protocols may require adjustment to fit the forest type and situations encountered. When writing a protocol, be as specific as possible to limit individual interpretation of the methods. On occasion judgment calls may be needed. In these situations, the decision should be recorded and incorporated into the protocol so that future situations are handled consistently. For example, CFRI institutes a maximum slope of 40% for new plots because surveyors walking around the plot can cause extensive soil erosion at higher slope angles. Another decision involved how to measure leaning tree DBH and height. In CFRI's protocol, DBH is measured at 4.5 ft as measured along the tree bole, regardless of height from the ground. Tree height is measured as distance from the ground to the tallest part of a tree, regardless of lean or if the top is dead. Depending on the project goals, these situations may be handled differently. A well-written protocol describes how to handle commonly encountered "grey area" situations.

Static protocols involve performing the exact same measurements at every plot. Dynamic protocols are flexible to accommodate changes based on the conditions within each plot. For example, a static protocol may require every tree to be measured within a 1/10th acre plot. A dynamic protocol may state that trees within half of a 1/10th acre plot may be measured if the plot is unusually dense. It is critically important to document plot size to accurately calculate tree metrics during data analysis. Dynamic protocols can save time, but also introduce an additional source of error into the dataset if changes in plot size are not properly recorded.

Photo credits: CFRI

DATA MANAGEMENT

Recording Data

Data can be collected using a number of different platforms ranging from paper datasheets, to rugged computers running excel or other data management software, to portable tablets running digital forms to collect and organize data. When choosing a platform, it is important to balance the tradeoffs between time spent in the field versus time spent in the office entering data, cost, expertise in setting up and using various programs, and data quality.

Paper datasheets require the least training and are fairly quick to collect data in the field, however they are prone to errors stemming from legibility as well as data entry errors in the office. Paper data can also require significant time to enter into digital platforms and check with quality assurance and control protocols.

Ruggedized computers typically require basic knowledge of Excel or other data entry platforms and produce digital datasets that are ready to be incorporated into data management systems with minimal data processing. Quality control measures can be built into data collection forms or templates. However, ruggedized computers can be cost-prohibitive and typographical errors can be impossible to trace to and correct.

Portable tablets are generally more affordable than ruggedized computers and data collection forms can be user friendly in the field. Quality control measures can be built into data collection forms. However, generating data collection forms requires expertise before data can be collected, and data processing after field collection generally requires coding expertise to format data to be consistent with data management platforms. Alternatively, some tablets support the use of spreadsheet software, but quality control measures are not as straightforward to implement. Similar to computers, typographical errors can be impossible to trace and correct when data collection forms or spreadsheet software are used.

Regardless of the platform used to collect data, care should be given to ensure data fields are congruent between data collection platforms and ultimate data storage platforms (e.g. "D.B.H." should not be a field label if "DBH" is used in a database designed to store that data). Additional consideration should be given ahead of time for desired precision, standardizing naming conventions for alphanumeric fields (plot names, species codes, decay class etc.). Many of these constraints can be set ahead of time on computers or tablets, reducing the amount and type of data cleaning required to ingest data into a database.

Data Storage

Data storage platforms for forest monitoring range from simple spreadsheets or workbooks to more complex relational databases. Similar to selecting a data collection platform, tradeoffs should be considered to balance the expertise required to manage data storage and the complexity of the monitoring program, as well as the types of analyses that are planned for the data.

Workbooks typically store data in multiple spreadsheets, where different datasets are stored in separate spreadsheets (e.g. tree data is one spreadsheet, fuels data is a different spreadsheet, etc.). Generally, workbooks and spreadsheets (such as Microsoft Excel, Google Sheets, Apple Numbers) are very user friendly but are designed to handle relatively small datasets. In addition to being a data storage platform, workbooks and spreadsheets provide a user friendly interface for basic data analysis and visualization. Smaller scale monitoring programs, such as those designed to evaluate forest management at the project scale, are best suited for data stored in workbooks and spreadsheets.

Relational databases (such as Microsoft Access, Oracle, MySQL) allow the user to manage numerous tables with relationships established between tables, enabling the user to generate more complex queries and ways of analyzing or summarizing data. The type of database used typically depends on the size of the dataset. For example, Microsoft Access is better suited for small to medium sized datasets, but may become sluggish for very large datasets where MySQL or similar would be a better performer. Microsoft Access is likely sufficient for most monitoring programs, readily available to most users, and uses a graphical user interface that most users can learn, albeit it is a steeper learning curve than Microsoft Excel. Because of this, the remainder of this section will focus on Microsoft Access when describing relational databases. Although Microsoft Access in not as user friendly as workbooks and spreadsheets, the relationships between tables, and their ability to handle larger datasets allows for more complex analyses at larger scales. For example, Microsoft Access will allow a user to query the data to pull tree data from all projects in a given forest type above a certain elevation threshold using a simple SQL query if desired. It should be noted, however, that Microsoft Access is not designed for data analysis or visualization, and the results of data queries are typically exported to different programs such as Excel, R, or Python for analysis and visualization. Because of its ability to hold larger datasets and create complex queries of inter-related datasets, Microsoft Access is best suited for larger monitoring programs, such as those that focus on landscape scales.

For monitoring programs focusing on the program-scale, choosing a data storage platform is a more challenging decision. As mentioned above, workbooks and spreadsheets are very user friendly but are limited in the size of datasets that are efficiently stored, and their ability to generate complex datasets aimed to answer more complicated questions beyond treatment effectiveness. Conversely, Microsoft Access has a much steeper learning curve, it takes time to set up numerous tables and relationships, and some level of management to query data from the platform for analysis. Choosing a data storage platform at these mid-level scales should consider the complexity of the questions being asked (e.g. do relationships between tables need to be established in order to conduct analysis?), the resources available in terms of expertise, and time available to devote towards data management in the office.

Structuring Data for Analysis

Monitoring data is typically analyzed using Excel (or some other spreadsheet software), statistical coding such as R or Python, and/or computer programs such as the Forest Vegetation Simulator. This section will focus on the use of Excel and R, as there is extensive existing documentation provided for using the Forest Vegetation Simulator to generate monitoring metrics. When choosing software to analyze and visualize monitoring data, it is important to consider the tradeoffs between ease of use, computing power, and statistical capabilities. While Excel is generally more user friendly than R and can do basic data manipulation and summaries, R is better suited for larger datasets that require more complex data manipulation and summaries and is a better option for customized data visualization and running statistics. Regardless of the tool chosen to perform data analysis, certain best practices should be followed in data structure to simplify analysis.

1. Data should be stored using a tabular structure, such that columns represent variables (e.g. DBH, height, etc.) or attributes (e.g. treatment type, sampling phase, species, etc.) and rows represent observations (e.g. 14.1, Mechanical, Pre, PIPO, etc.).
2. Analytical objectives should be clearly thought out and represented in the data. For example, if comparing average DBH for treated vs non-treated areas is an objective, each record (tree) should have a column for the plot it is associated with, it is DBH measurement, and it is associated plot type (Treatment vs Control). Similarly, if knowing DBH by species is of interest, and additional column should be included describing the tree species.
3. Data should be structured as simply as possible. Each observation (row) should have each measured variable as a separate column (species, DBH, height, etc. should all be separate). Avoid merging cells or creating nested tables that make it challenging to summarize data.

Below is a basic, hypothetical example of how to compare monitoring metrics (average DBH and tree density) for treated vs control areas of a project using both Excel and R. Note the raw data structure (Figure 7), in which each tree occupies a single row, and different variables are recorded for it (associated plot, treatment type, species, DBH, calculated density contribution (for a 1/10th acre plot).

PlotCode	PlotTreatmentStatus	Species	DBH	CalcCol_DensityContribution
NCW–1C3–01	Control	PIPO	12.0	10
NCW–1C3–01	Control	PIPO	13.1	10
NCW–1C3–01	Control	PIPO	15.0	10
NCW–1C3–01	Control	PIPO	19.2	10
NCW–1T1–01	Treatment	PIPO	15.1	10
NCW–1T1–01	Treatment	PIPO	13.4	10
NCW–1T1–01	Treatment	PIPO	17.1	10
NCW–1T1–01	Treatment	PIPO	15.6	10
NCW–1T1–01	Treatment	PIPO	17.3	10

Figure 7. Example raw data structure used to calculate summary statistics by treatment type.

Using this data structure, calculating summary statistics by treatment type can be easily accomplished in Excel using a pivot table, such that PlotCode is set to rows, columns are set to PlotTreatmentStatus, and values are set to “Average of DBH” and Sum of “CalcCol_DensityContribution.” This returns average DBH per plot, and trees per acre per plot (Figure 8). Average values for treatment vs. control can be calculated in excel, using the “Average” function and selecting the appropriate cells for each treatment type.

	Column Labels					
	Control		Treatment		Total Average of DBH	CalcCol_Density Contribution
Row Labels	Average of DBH	Sum of CalcCol_DensityContribution	Average of DBH	Sum of CalcCol_Density Contribution		
NCW-1C1-02	6.2375	80			6.2375	80
NCW-1C1-03	8.715789474	380			8.715789474	380
NCW-1C1-04	8.702	500			8.702	500
NCW-1C1-05	7.6	50			7.6	50
NCW-1C2-06	6.7	210			6.7	210
NCW-1C2-07	9.56	300			9.56	300
NCW-1C2-08	12.32307692	130			12.32307692	130
NCW-1T1-01			13.56428571	140	13.56428571	140
NCW-1T1-02			9.88	100	9.88	100
NCW-1T1-03			9.815384615	260	9.815384615	260
NCW-1T1-04			9.837037037	270	9.837037037	270
NCW-1T1-05			6	110	6	110
NCW-1T1-06			7.133333333	30	7.133333333	30
Grand Total	**9.133962264**	**2120**	**9.666425993**	**2770**	**9.435582822**	**4890**

Figure 8. Pivot table showing average DBH for control and treated areas, and calculated trees per acre (CalcCol_DensityContribution).

Conversely, the same can be accomplished using the dplyr package in R with the following script to calculate values at the plot level (output in Figure 9):

```
PlotSummary <- ddply(data, .(PlotCode, PlotTreatmentStatus), summarize,
                     averageDBH = mean(DBH),
                     TreesPerAcre = sum(CalcCol_DensityContribution))
```

PlotCode	PlotTreatmentStatus	averageDBH	TreesPerAcre
NCW-1T1-05	Treatment	6.000000	110
NCW-1C1-02	Control	6.237500	80
NCW-1T1-09	Treatment	6.620000	50
NCW-1C2-06	Control	6.700000	210
NCW-1C2-10	Control	7.130000	200
NCW-1T1-06	Treatment	7.133333	30

Figure 9. Data summarized to the plot level showing average DBH and trees per acre calculated using R. Summaries were calculated using R version 4.3.2 and version 1.8.9 of the plyr package. Be aware that future versions of R or the plyr package may require differ syntax.

The following script is used to calculate treatment-level values:

```
TreatmentSummary <- ddply(PlotSummary, .(PlotTreatmentStatus), summarize,
                          AverageDBH = mean(averageDBH),
                          TPA = mean(TreesPerAcre))
```

PlotTreatmentStatus	AverageDBH	TPA
Control	9.307331	212.0000
Treatment	9.734428	197.8571

Figure 10. Plot data summarized to the treatment level showing average DBH and trees per acre for control vs treated stands. Data summarized with R. Summaries were calculated using R version 4.3.2 and version 1.8.9 of the plyr package. Be aware that future versions of R or the plyr package may require differ syntax.

A full tutorial in data analysis is beyond the scope of this handbook, however, these examples highlight the importance of having well-structured data that will allow the user to summarize measurements of interest by important attributes such as species, treatment type, etc.

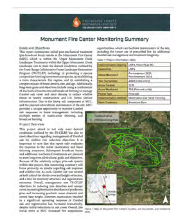
Photo credit: CFRI

REPORTING AND EVALUATION

Summarizing monitoring results in reports and presentations is essential for documenting and communicating forest management outcomes. Furthermore, reporting monitoring results creates opportunities for collaborative discussions that evaluate monitoring results and facilitate the learning and adjusting phase of adaptive management. While the primary purpose of this handbook is to provide guidance on field-based data collection methods, here the Monitoring Handbook concludes by providing brief guidance on reporting and evaluation.

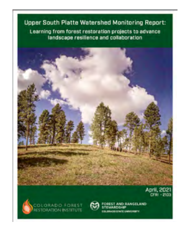
Reporting

An important part of the adaptive management process is summarizing monitoring results in written reports to document and communicate findings. Effective reports include a description of the project goals, management actions, monitoring questions, data collected, results, and interpretation or conclusions. Reports should clearly articulate monitoring results with figures, photos, and written descriptions. Because this process is crucial to a successful monitoring program, reporting should be completed on a regular schedule (e.g. annually). Here are a few examples of monitoring reports that CFRI has published:



The Monument Fire Center Monitoring Summary (Barrett et al, 2024) is an example of a monitoring summary for a single project that is meant to be brief. This type of report is focused on presenting monitoring results and offers highlights and conclusions but does not offer an extensive interpretation of the results. Monitoring summaries are an excellent tool to quickly share management outcomes with partners and facilitate adaptive management discussions during presentations, collaborative meeting, and field tours.

The Elkhorn 4 Prescribed Fire Monitoring Report (Morici and Gannon, 2021), and the Pole Hill Monitoring Report (Hunter et al, 2022) are examples of monitoring reports on a single project but include more detail, analysis, and interpretation of the results. Detailed monitoring reports are framed after peer-reviewed journal articles in scientific publications.



The Upper South Platte Monitoring Report (Slack et al. 2021) is an example of a large report that includes many projects. The purpose of this report is to evaluate the outcomes of collaborative forest management within the Upper South Platte Partnership and the Forest to Faucets initiative, and is a program level monitoring report. This type of report can be produced less frequently but is more comprehensive and documents many management actions over a period of time.

In addition to developing formal written monitoring reports, oral presentations are also an effective way to communicate monitoring results to affected entities and promote adaptive management. Oral communication should have the same components as effective written reports and be presented as concisely as possible. CFRI has found that oral communication in a formal setting, such as an annual monitoring meeting, as well as informal presentations during field trips can be effective to facilitate learning and discussion. In general, some combination of written and oral reporting is an practical way to reach as diverse an audience as possible.

Evaluation

The final step of the adaptive management process is evaluating the information gathered and assessing 1) did management actions result in goals being met, and 2) if the existing goals, shared values, or desired conditions should be modified. Using quantitative data to assess whether forest management outcomes, such as changes in forest density or understory species diversity, met stated project objectives helps refine management practices to achieve targets. Tracking results over time allows forest managers to respond to changing conditions. The end goal of monitoring is transforming raw data into locally relevant, actionable insights that inform future forest management.

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APPENDIX A: SAMPLE DATA COLLECTION PROTOCOLS

This protocol is designed by the Colorado Forest Restoration Institute (CFRI) to collect comprehensive data for changes in non-spatial forest structure and composition as a result of management actions in forests and woodlands of Colorado. This protocol establishes plots using random plot locations, measures trees within a 1/10th acre fixed radius plot. It is an example of the level of detail to include in written field protocols. Data is collected in a pre-built Survey123 form.

Data Collection Protocols

PLOT LAYOUT

1. **Navigate to the plot.** If resampling an area, use the site map, GPS coordinates, and/or plot photos to navigate to the plot. If establishing a new plot, use Avenza map or GPS coordinates. When establishing a new plot, make sure that the GPS point falls in an area that is suitable (e.g. not on a road, project boundary, etc.) and characteristic of the surrounding area. If the plot needs to be moved, use the random number table/generator to choose a direction and distance to move the point to a suitable area. Before proceeding, be sure that the edge of the plot is at least 100 ft from the project boundary.

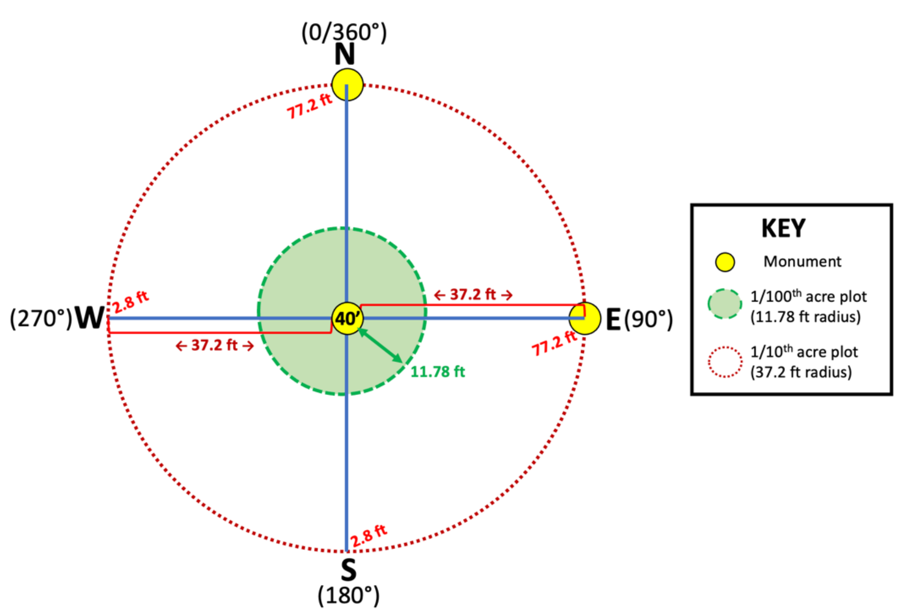
   Helpful hints for relocating a plot:

   - Use the metal detector.
   - Plug coordinates into the GPS – occasionally points on the map can be off.
   - Match the plot location using previous plot photos. Look for distinctive rocks, branches, snags, topography, etc.

2. **Lay out the plot**. From plot center, establish 4 transects in the cardinal (0°, 90°, 180°, 270°) directions using a **declinated** compass (set - 8.5° east for the Front Range) and two 100 ft tapes. Center the 40 ft mark of both tapes over the plot center and extend tapes to 78 ft. Clip tapes together with a binder clip at plot center to ensure they stay in place. Be sure the 0 ft mark is on the S and W ends of the transects (the reel should be on the N and E ends). Colored tape marks the plot center and transect ends.

   [Note that this protocol can be implemented with 50 ft tapes, but care must be taken to ensure measurements happen at the correct locations.]

3. **Monument.** Install permanent markers, or monuments, using a nail, yellow painted washer, and a silver "CFRI Long-term Monitoring Plot" tag. Monuments should be located at plot center, 77.2 ft on the north transect, and 2.8 ft on the east transect. Inscribe plot name and location on the tag with a pen and write it on the washer with a permanent marker. Wrap a piece of pink flagging around each washer. Re-flag nails on each revisit or once per year.



PLOT SET-UP

1. **Basic Plot Information**
   a. **Plot Name:** Triple check that the plot name is correct! Look at the map and compare tablets. Errors in plot names cascade to all data and are very difficult to fix later.
   b. **Aspect:** Using a declinated (8.5˚E) compass, measure the hillslope aspect in degrees (0-359) within the 1/10th acre plot. This is NOT along the transect, but where a ball would roll down the hill. If revisiting, record the previously measured aspect unless it is outside of revisit standards. Revisit aspect accuracy standards: ± 15°
   c. **Slope:** Using a clinometer, record the slope of the hillside along the aspect to the nearest percent within the 1/10th acre plot. Take slope measurements from plot center both downhill and uphill and record the average slope of the two measurements. In general, new plots should not be installed when slope >40%. If revisiting, record the previously recorded slope unless it is outside of the revisit standards. Revisit slope accuracy standards: ± 5%
   d. **Coordinates:** Record the location (UTM) and elevation (ft) using the built-in function on the Survey123 form. Revisit UTM accuracy standards: ± 5 m E & N
   e. **Fuel Model:** (Crew Leader/Senior Technician) assign a fire behavior fuel model to the plot using the Fuel Model Key.
   f. **Plot Notes**: Record any plot notes in the Survey123 form, including notes on plot location (near road, near project boundary), making specific notes of past disturbances (e.g. fire, insect outbreaks, stumps from logging, animal signs/grazing, human disturbance, etc.).
2. **Photos**
   a. Standing at the plot center, take 6 photos. Fill out a white board with the plot name and date. Hold whiteboard 10 ft from plot center. Take photos in the landscape orientation, frame photos so the white board is legible, and exclude gear and people in the shot. *For post-treatment plots, check pre-treatment photos to ensure the same view is captured.* The photo sequence is:
      1. **Ground, North:** Face the north transect and hold the tablet at eye level while standing about 5 ft back from plot center. Angle the tablet downward to include the entire 1 m^2 sampling frame and plot center in the photo; making sure that the transect is in the center of the photo.
      2. **Eye level, North:** Hold the tablet over plot center, looking along the north transect at eye level.
      3. **Canopy, North:** Hold the tablet over plot center, looking along the north transect towards the upper tree canopy.
      4. **Eye level, East:** Hold the tablet over plot center, looking along the East transect at eye level.
      5. **Eye level, South:** Hold the tablet over plot center, looking along the South transect at eye level.
      6. **Eye level, West:** Hold the camera over plot center, looking along the West transect at eye level.

PLOT MEASUREMENTS

For all plot measurements, begin sampling on the north transect and move clockwise through the plot.

Tree Overstory

1. **Fixed radius plot:** 1/10th acre plot (37.2 ft radius).
2. **Flag trees in plot:** Tree overstory includes: all live and dead trees ≥ 4.5 ft tall, with a diameter at breast height (DBH) ≥ 5.0 in, and the center of the tree is within 37.2 ft of plot center. Flag all trees meeting these requirements using alternate pin flag colors (color choice does not matter), starting to the east side of the north transect and working clockwise. Since trees are not always tagged, **it is essential that trees are recorded in order** to understand changes in tree overstory. If one tree is in front of another but both are in the plot, measure the furthest from plot center first. Use extra 100 ft transect tape to check whether the center of the bole of a boundary tree is within the plot.
3. When conducting **post-treatment measurements**, check for any new or missing trees and make note of any changes in tree order in the notes for each tree.
4. **Measurements for each tree**:

Species	**Record species of each tree.**
Status Class	L= Live trees with green needles. 1a *with needles* = Recently dead trees, top intact, needles/foliage and fine branches present. 1b *without needles* = Recently dead trees, top intact, fine branches present. 2 = Snags with coarse branches, but fine branches and foliage have fallen off. 3 = Rotten snags. Very few if any branches remain. Usually short (<20 ft) due to decay status.
Diameter at Breast Height (DBH)	Measure the distance from the top of mineral soil to breast height (54 inches) with a measuring tape on the uphill side of the tree. **Mark this measuring location with timber crayon**. If a tree is leaning, arrange the tape so that it goes along the length of the tree and measure DBH perpendicular to the central axis. *Measure to the nearest 0.1 inch.*
Height	Ocular estimate up to 10 ft. Use rangefinder/ hypsometer for heights taller than 10 ft, making sure that the value returned seems reasonable. *Measure to the nearest foot.*
Crown Base Height (CBH)	Lowest height of continuous needles/leaves for all live trees. *Measure to the nearest foot.*

Special cases:

- Multiple qualifying stems: If a single tree has multiple stems that divide below DBH (4.5 ft or 54 inches) – very common in juniper and pinyon pine – consider each qualifying stem (DBH ≥ 5 in) as its own tree (take all measurements and tag if tagging trees).

Tree Seedlings and Saplings

1. **Tree Seedlings**: live trees within the 1/100th acre plot (11.78 ft radius) that are less than 4.5 ft tall.

   Record the species and number of individuals in each height class:

   Class 0: Germinants
   Class 1: 0 – 4 in
   Class 2: 4.1 – 18 in
   Class 3: 18.1 – 30 in
   Class 4: 30.1 – 54 in

2. **Tree Saplings**: live trees within the 1/100th acre plot (11.78 ft radius) that are 4.5 ft or taller with DBH < 5 in. For every sapling, record the same measurements as overstory trees (see page before).


Photo credit: Andrew Slack

Field Data Collection Sheets

Plot Information

Project	Plot ID	Sampling date	UTM N	UTM E	Elevation	Slope	Aspect	Fuel Model	Notes

Tree and Sapling Datasheet

*Record trees and saplings on separate data sheets

Plot ID	Tree or Sapling #	Species	Status	DBH	Height	CBH	Notes

Seedling Datasheet

Plot ID	Species	Height Class	Count

APPENDIX B: ADDITIONAL RESOURCES AND PROTOCOLS

Additional Resources

Forest Inventory and Analysis protocols: highly detailed protocol that describes data collection for sites, trees, down woody material, soils, and understory vegetation. https://www.fs.usda.gov/research/sites/default/files/2024-02/wo-v9-3_sep2023_fg_nfi_natl.pdf

FS Veg (USFS Common Stand Exam): forest inventory protocol desgined to guide prescription development. https://www.fs.usda.gov/nrm/fsveg/index.shtml

Bureau of Land Management Assessment Inventory and Monitoring (AIM) Methods: monitoring guidelines focused on grassland, shrubland, and savannah ecosystems; includes detailed understory data collection methods. https://www.blm.gov/sites/blm.gov/files/docs/2022-04/TR_1734_8_vol1_508.pdf

National Park Service Fire Monitoring Handbook: comprehensive instructions for developing a monitoring program and methods to monitor fire behavior and effects. https://www.nps.gov/orgs/1965/upload/fire-effects-monitoring-handbook.pdf

Fire and Fuels Extension to the Forest Vegetation Simulator: models fuel dynamics and potential fire behavior with user input stand data. https://www.fs.usda.gov/fmsc/ftp/fvs/docs/gtr/FFEguide.pdf

Additional CFRI protocols

COSWAP forest inventory protocol: forest structure and composition, woody fuels, and fire hazard protocols used for monitoring the Colorado Strategic Wildfire Action Program (COSWAP). https://cfri.colostate.edu/wp-content/uploads/sites/22/2023/09/COSWAP-Inventory-Protocol-2023.pdf

Simple plot protocol: collect comprehensive data for ground, surface, herbaceous, shrub, and tree fuels to determine changes in fuel abundance and distribution. https://cfri.colostate.edu/wp-content/uploads/sites/22/2023/09/Simple-Plot-Protocol-2023-v2.pdf

Mothership plot protocol: collect comprehensive data for changes in non-spatial forest structure and composition, fuels and fire potential, and plant species abundance and diversity. https://cfri.colostate.edu/wp-content/uploads/sites/22/2023/09/Mothership-Protocol-2023-v2.pdf

Immediate post-burn mothership protocol: captures fire severity and effects within 2 months of a prescribed fire or wildfire, including substrate and vegetation burn severity, factors affecting tree mortality, and fine woody fuels. https://cfri.colostate.edu/wp-content/uploads/sites/22/2022/05/RxMothership-Immediate-Postburn-Protocol-2020.pdf

Habitat protocol addendum: captures abundance and quality of woody habitat structures within forest stands. https://cfri.colostate.edu/wp-content/uploads/sites/22/2023/09/Habitat-Protocol-Addendum_PDF.pdf

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