Mulching: A knowledge summary and guidelines for best practices on Colorado's Front Range

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CFRI — 2001

COLORADO FOREST RESTORATION INSTITUTE

FOREST AND RANGELAND STEWARDSHIP

COLORADO STATE UNIVERSITY

SOUTHERN ROCKIES FIRE SCIENCE NETWORK

Front Range Fuels Treatment Partnership Roundtable

A masticated stand on the South Platte Ranger District.

Colorado Forest Restoration Institute

The Colorado Forest Restoration Institute (CFRI) was established by Congress in 2005 through the Southwest Forest Health and Wildfire Prevention Act as an application-oriented, science-based outreach and engagement organization hosted by the Department of Forest and Rangeland Stewardship and the Warner College of Natural Resources at Colorado State University. We lead collaborations between researchers, managers, and stakeholders to develop, synthesize, and apply locally-relevant, actionable knowledge to inform forest management strategies and achieve wildfire hazard reduction goals in Colorado and the Interior West.

Front Range Roundtable

The Front Range Roundtable Fuels Treatment Partnership convened in 2004 in response to the worst fire season in Colorado's recorded history in 2002. The Roundtable is a coalition of individuals from state and federal agencies, local governments, environmental and conservation organizations, the academic and scientific communities, and industry and user groups, all with a commitment to forest health and fire risk mitigation along Colorado's Front Range.

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Document Development and Acknowledgments

In the fall of 2014, the Front Range Roundtable identified the need for best management practice guidelines on chipping and mastication on the Colorado Front Range. To meet this need, during the quarterly Roundtable meeting on November 14th, 2014, Dr. Monique Rocca (Colorado State University), Dr. Mike Battaglia (Rocky Mountain Research Station), Jill Welle (Douglas County), and Brett Wolk (Colorado Forest Restoration Institute) led a discussion on the utility, effectiveness, goals, and objectives of mulching techniques. In February 2015, a sub-team that included participation from around a dozen agencies developed a draft document. This draft was presented and discussed with the Roundtable at the quarterly meeting on February 20th, 2015, when additional feedback was incorporated. Feedback from these Front Range Roundtable meetings and subsequent conversations with stakeholders over the years have greatly informed the final document, and we thank Roundtable members for their thoughtful insights and considerations. These guidelines were collaboratively developed by the Colorado Forest Restoration Institute and the Southern Rockies Fire Science Network for and with the Front Range Roundtable. We thank Corey Gucker and Lael Gilbert for providing useful feedback on earlier drafts of this paper. Hannah Brown gave insightful feedback on the text and creatively designed the layout and document graphics.

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*We were extremely fortunate to work with Chuck Dennis on this project before his passing in 2019, and are remiss that he was not able to see the final publication and product of his hard work. He provided an unparalleled wealth of knowledge about mulching practices, and offered a steady voice of reason to help us find agreement and positive outcomes from the most challenging conversations.

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Highlights

- Mulching is classified into two broad categories—*chipping* and *mastication*—which have different operational, ecological, and fire characteristics.
- Deep areas of mulch can suppress plant growth and establishment. However, mulch depths and distributions in wildland vegetation applications across Colorado rarely exceed thresholds that negatively impact plant abundance, tree establishment, or significantly degrade soil nutrient properties.
- Mulching techniques can add significant amounts of woody material to the soil surface. This material persists and remains flammable for at least 10 years in most Colorado forests.
- Rearranging biomass from standing to mulched on the ground can change fire behavior from a crown fire to burning on the surface, which provides more potential opportunities for fire suppression. However, the additional woody material can also increase surface fire duration and intensity, complicating fire containment and magnifying post fire tree mortality and ecological impacts.
- Establishing clear project goals and objectives will aid in determining mulching project specifications. The sole metric of "average mulch depth" is often insufficient management planning detail to achieve desired mulching project outcomes. We suggest five mulch depth and distribution specifications (with specific target ranges) to help maximize benefits of mulching tools and improve communication of project goals with contractors and project stakeholders.

    1. Distribution of mulch (e.g. *XX*–*XX*% of the management area will be covered with mulched material).
    2. Maximum allowable mulch depth (e.g. woody material shall not exceed *XX* inches within any part of the management area).
    3. Maximum mulch patch size (e.g. continuous mulch cover will not exceed *XX* area).
    4. Maximum size of mulch pieces (e.g. wood pieces will not exceed *XX* diameter and *XX* length).
    5. Average mulch depth (e.g. mulch depths will average *XX* inches across the management area).

- Chipping and mastication tools are often more successful at accomplishing project objectives when they are used in combination with other vegetation management strategies.
- The largest knowledge gaps remain in our understanding of wildlife response to mulching, fire behavior and effects when mulch burns, and long term (10 years or more) trends in mulched areas.

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Introduction

Mulching involves the use of heavy equipment to grind, shred, chip, or chop large woody material into smaller pieces. Mulching activities such as chipping and mastication have been relied-upon tools in forest management on the Front Range of Colorado and throughout the United States since the late 1990s (e.g. Hood and Wu 2006, Owen et al. 2009, Wolk and Rocca 2009, Battaglia et al. 2010, Gottfried and Overby 2011, Kreye et al. 2014, Jain et al. 2018). ***Chipping*** and ***mastication*** are specific types of mulching, and these techniques each have fundamental differences in operational constraints, ecological effects, and potential fire behavior (Table 1). Mulching can be used alone, or in combination with other management activities (e.g. multi-staged understory and overstory vegetation management, timber harvests, prescribed fire, site preparation, etc.).

In the fall of 2014, the Front Range Roundtable identified the need for best management practice guidelines on chipping and mastication on the Colorado Front Range. These guidelines were collaboratively developed by the Colorado Forest Restoration Institute and the Southern Rockies Fire Science Network for and with the Front Range Roundtable. A wide range of professionals contributed their expertise and perspectives to this project.

The purpose of this document is to clarify the benefits and limitations of mulching, and to inform planning of mulching projects in forests and woodlands along the Colorado Front Range. This synthesis is not meant to be a comprehensive planning document for choosing amongst different vegetation management techniques. Developing a thorough plan—complete with project specifications and expected outcomes—will help you to determine if mulching would be an appropriate and useful tool for accomplishing your resource management goals. The Front Range Roundtable recommends considering the information and planning insights in this document for guidance on designing, implementing, and monitoring mulching activities within the Colorado Front Range. Many additional resources exist to aid in considering other management techniques, and we suggest leveraging these resources as you assess the wide range of other vegetation management tools available to achieve your project objectives.

It is important to note that there is no proxy for widely distributed chips or masticated wood in natural ecological processes. In addition, differences in equipment, project specifications, as well as variability in operator skill and experience, can result in very

Helpful Definitions

Mulching: *a general term* for using both light and heavy equipment to grind, shred, chip, or chop woody material into smaller, variable pieces. Mulching does not reduce total site biomass, but reconfigures it, usually from the tree canopy to the surface.

Chipping: *a type of mulching* that involves feeding woody biomass into a wood chipper, which grinds or axes the material inside the machine and sprays it out as uniform-sized chips. Chipped material can be spread on site, piled for later removal, or blown into a truck or container and hauled away. On-site distribution can be controlled by positioning the exit chute or machine. Chipping machines are often pulled behind trucks or other large equipment, though larger machines can be self-propelled and have an articulating arm that feeds material into the integrated chipper. Chipping does not reduce total site biomass unless hauled away.

Mastication: *a type of mulching* that shreds, grinds, or chops woody material in place and deposits mulch onto the soil surface. Mastication produces variable-sized materials—from small shreds to sections of whole tree trunks—and the distribution is more difficult to control than chipping. There are many types of masticating machines: horizontal and vertical rotating shafts, rotary blades, drums, chain flails, articulating arms, and other variations. Each of these masticate or grind woody vegetation somewhat differently, but they all have similar advantages, limitations, and ecological impacts compared to chipping.

different outcomes for mulch depth and distribution (Windell and Bradshaw 2000, Jain et al. 2018). Mulching implementation techniques and equipment continue to evolve, as does our knowledge of the science and practice of mulching. There is a growing body of work on the ecological effects and changes to fire behavior in mulched areas, and much we can learn from existing forest science research and implementation experience.

Science Summary

During mulching operations, biomass is redistributed from the canopy to the surface, and is not removed from the project site. Recent research suggests this can have potential localized effects on ecological processes such as plant community composition, tree and shrub regeneration, soil moisture content, and nutrient cycling (e.g. Battaglia et al. 2010, Kreye et al. 2011, Rhoades et al. 2012, Brewer et al. 2013, Kreye et al. 2013, Fornwalt et al. 2017). Field studies (Keane et al. 2018, Jain et al. 2018) and field observations (e.g. Wolk and Rocca 2009) indicate that different types of mulching equipment—which produce different mulch sizes and distributions—result in different implications for ecological impacts, potential fire behavior, and post-fire outcomes. Ecological impacts to soil and plant communities are especially pronounced in small areas with deep mulch (e.g. Miller and Seastedt 2009), although average mulch depths and broad ecological impacts across treatment units are typically low in forests on the Colorado Front Range (Wolk and Rocca 2009, Battaglia et al. 2010, Rhoades et al. 2012, Fornwalt et al. 2017).

Because research on the ecological effects of mulching is relatively new, long-term effects are still uncertain. How mulching impacts unfold in short to medium time frames (up to 10 years) is becoming more clear, though there are still many important questions that remain unanswered. For example, there is a scarcity of information on wildlife interactions, or fire within mulched areas.

While some impacts of mulching remain unknown, these vegetation management tools have great potential for managing fire adapted landscapes. Rearranging biomass from standing to mulched on the ground can change fire behavior from a crown fire to burning on the surface, which provides more potential opportunities for fire suppression. However, the additional woody material can also increase surface fire duration and intensity, complicating fire containment and magnifying post fire tree mortality and ecological impacts. As Knapp et al. (2011) summarize, "under severe fire weather conditions, fire behavior and effect models as well as observations from wildfires suggest that mastication may be more effective for moderating fire behavior than reducing residual tree mortality. Treating masticated fuels with prescribed burns could potentially improve the resilience of stands to wildfire."

Mulch impacts on ecology, soils, and fuels

The effects of managing forests to reduce woody plant density and tree cover have been well documented. No matter the method, reducing woody plant density: increases the availability of resources (light, water, and nutrients) for both existing vegetation and future regeneration; creates soil disturbances; reduces canopy fuels; and increases wind exposure and fuel drying. All of these effects have the potential to alter wildlife habitat, change how nonnative species are introduced and spread, and impact forest processes such as erosion and fire behavior. While mulching does remove trees and shrubs, this document does *not* delve into detail about the general effects of removing standing woody vegetation from an ecosystem. Instead, we focus on the unique impacts of the addition of mulched woody biomass to the soil surface.

Research has shown that deep, localized patches of mulched material, particularly from broadcast chipping, suppresses vegetation (Fornwalt et al. 2017, Miller and Seastedt 2009, Wolk and Rocca 2009, Cueno 2011, Battaglia et al. 2010), and can alter nutrient cycling for the first few years after mulching (Miller and Seastedt 2009, Rhoades et al. 2012). However, these impacts are often highly localized because mulch distribution is usually patchy and average mulch depth is typically low across management areas in the Colorado Front Range (Battaglia et al. 2010, Fornwalt et al. 2017, Wolk and Rocca 2009). Other short term impacts, similar to those of any forest mechanical treatment, may last several years and are summarized below.

Herbaceous Vegetation

Several studies have shown that herbaceous plant abundance is locally suppressed by deep mulch layers, but overall herbaceous plant abundance on mulched sites is similar to—or greater than—untreated areas. Chipped or masticated biomass depths exceeding roughly 3 inches (7.5 cm) in any one location will typically limit herbaceous vegetation establishment. In Front Range forest and woodland systems, mulch depths greater than about 6 inches (15 cm) fully suppress understory plant growth (Battaglia et al. 2010, Fornwalt et al. 2017, Wolk and Rocca 2009, Cueno 2011). Chipping has the potential to suppress veg-

Choose the Right Tool For the Job: Mulching Equipment Strengths and Challenges

Examples of chipping equipment and resulting mulch:


Morbark

Examples of mastication equipment and resulting mulch:


Kari Greer, USFS


USFS

Table 1. Key differences between chipping and mastication

Considered Variable	Chipping	Mastication
Mulch Size	Uniform	Variable
Control over mulch depth and distribution	High	Low
Operability on difficult terrain	Low (unless using a tracked machine)	High
Work rate	Slower	Faster
Cost	Generally higher, labor intensive	Generally lower, higher equipment cost but lower labor costs
Physical soil disturbance from mulch	Minimal	Moderate to high
Biomass utilization opportunities	Yes, can be removed off site	None, all material remains on site
Fuelbed compaction	Very compact	More compact than a natural fuelbed, but less compact than fuelbed created by chipping

Different types of equipment and operator skill/experience can result in very different outcomes for mulch depth and distribution. It is important to understand the tradeoffs associated with different types of mulching equipment and their inherent limitations in order to determine what type of mechanized equipment is appropriate for a successful project (see Table 1). In general, the type of equipment used is less of a factor for the resulting size and distribution of masticated material than equipment operator technique and technical project oversight.

There are a wide variety of masticating machines that grind woody vegetation differently, including: horizontal and vertical rotating shafts, rotary blades, drums, chain flails, and articulating arms. Despite their differences, these types of machines generally have similar advantages, limitations, and ecological impacts. Costs of operating these machines can vary widely, but ecosystem effects and fire behavior may not (Lyon et al. 2018). A variety of masticating machines can accomplish similar ecological and fuel distribution results. We suggest providing clear project specifications, and asking for references and viewing examples of work to verify operator ability.

While operator technique can have a large impact on mastication results, there remain fundamental differences between chipping and mastication as outlined in Table 1. Chipping will always produce uniform sized pieces of mulched woody material regardless of operator experience or skill, while piece size of masticated material can vary widely based on operator discretion. The depth and distribution of chipped material is much more easily controlled with chipping operations compared to mastication, although chipping often results in locally deep mulch beds if the discharge chute is not moved. Chipping machines are easier for low-skilled operators compared to mastication machines. It is still largely unknown what the implications of the differences between chipping and mastication are for ecological and fire impacts, but these methods and resultant mulch characteristics likely lead to different ecological and fire outcomes, and more research is needed (e.g. Wolk and Rocca 2009, Keane et al. 2018).

etation for longer periods due to the more compact nature of material and a higher likelihood for localized deep patches of mulch. Mastication generally results in wider dispersal of mulch, looser packing of woody biomass, and quicker herbaceous plant recovery than chipping.

While herbaceous vegetation is often suppressed the first few years after mulching (Miller and Seastedt 2009), understory plant abundance across an entire mulched area generally reaches levels comparable to—or greater than—harvested/un-mulched sites or unharvested forests within 3 to 5 years (Wolk and Rocca 2009, Battaglia et al. 2010, Coop et al. 2017, Fornwalt et al. 2017, Owen et al. 2009). Battaglia et al. (2010) found that median mulch depths across the Front Range measured 1 to 2.5 inches (2.5-6 cm). The deepest pockets of chipped or masticated materials commonly occur in mid-elevation mixed conifer forests, but even in these habitats, deep woody material was relatively rare and localized. Because deep patches are rare and there is a low median depth of mulch across much of Colorado's Front Range landscape, plant suppression is also localized to small areas with deep mulch, and is generally not considered a concern over large areas.

Mulching has been found to change the plant species composition of forest and woodland areas compared to both unharvested areas and harvested/un-mulched areas. In chipped areas, plants that spread vegetatively are more abundant than those that spread by seed dispersal (Wolk and Rocca 2009). Fornwalt et al. (2017) found that mastication increased herbaceous vegetation abundance and species diversity compared to unmanaged forests across a variety of forest ecosystems in Colorado.

Some studies have documented significant increases in non-native vegetation following mulching (e.g. Coop et al. 2017, Owen et al. 2015). However, this effect is not limited to mulched areas. Exotic species abundance also tends to increase following other types of mechanical forest treatments and fire disturbances, with this response heightened as treatment intensity increases (e.g. Metlen et al. 2006, Abella and Springer 2015). Areas with high native species diversity also contain more non-native species (Stohlgren et al. 2002, Fornwalt et al. 2003). Overall, while chipping or mastication may change plant community composition, there is little evidence that mulching generally exacerbates invasion by non-native species significantly more than other common forest management techniques.

Tree and Shrub Regeneration

Chipping and mastication activities do not seem to suppress conifer seedling establishment and growth across the landscape, and conifer tree regeneration in mulched areas is similar to or greater than untreated stands (e.g. Battaglia et al. 2010). Studies suggest that conifer tree regeneration in mulched areas is sufficient for reforestation and is not negatively impacted by mulching activities, except in very localized areas. Replanting in mulched areas is typically unnecessary to sustain forest cover, especially if some overstory is retained.

Throughout the Front Range, small tree seedling (<6 in/15 cm tall) densities were greater in the mulched forests than similar adjacent untreated forests 6 to 9 years after mulching activities (Battaglia et al. 2015). At a site in Boulder County, Wolk and Rocca (2009) found no seedling establishment 3 to 5 years after sites were either thinned and chipped, or thinned with biomass removed, suggesting that conditions other than broadcast chipping were influencing tree regeneration success. In ecosystems across Colorado, tree seedlings are able to establish in mulch depths of up to 6 inches (15 cm), but preferentially established in depths of less than 2 inches (5 cm) (Battaglia et al. 2015). These studies suggest that managers should anticipate natural tree regeneration, and perhaps even prolific regeneration, on some mulched sites depending on tree species, climate, and site conditions.

Resprouting species—such as aspen, Gambel oak, serviceberry, and other brush species—can respond vigorously to mulching. In some cases, the densities of resprouting species can reach pre-treatment densities within the first post-treatment growing season (Battaglia et al. 2010). At one site in Douglas County, resprouting Gambel oak reduced any fire mitigation benefits within 2 growing seasons (Morici et al. 2019). However, a persistent decrease in resprouting species was observed in other studies in pinyon-juniper-Gambel oak systems of the far southern Front Range (Coop et al. 2017). Differences in soil and climate likely explain the variability in Gambel oak response to mastication, but variability in Gambel oak response is a knowledge gap that needs further investigation. Early post-treatment monitoring of sprouting and growth rates on these sites is critical, as is planning for follow-up and maintenance treatments (Battaglia et al. 2010). A more comprehensive resource summarizing knowledge for Gambel oak ecology and management in the southern Rockies can be found in Kaufmann et al. (2016).

Mulch Fuel Loading and Persistence

Mulching treatments decrease canopy fuel hazard, often with substantial increases in surface fuel loading. In Colorado, surface fuel loading was 3 to 6 times greater in mulched forests compared to untreated forests (Battaglia et al. 2010). This increase is similar to those found in other regions (Bradley et al. 2006, Kreye et al. 2014). Mulching activities change the makeup and distribution of materials on the forest floor from predominantly large woody debris or heavy fuels (> 3 in/7.5 cm in diameter) with substantial amounts of needle and organic litter, to a more uniform and continuous fuelbed of small, irregularly shaped pieces of wood (< 1 in/2.5 cm in diameter) with less needle and organic litter (Battaglia et al. 2010). Depending on the volume of mulched material deposited, this small wood often forms a dense, compact, and more continuous fuelbed.

Fuel loads remain higher when compared to untreated Colorado forests 6 to 9 years after treatment (Battaglia et al. 2015). However, Battaglia et al. (2015) also found that mulched materials lost 50%-80% of their mass after 6 to 9 years, which indicates that fuel decomposition is occurring, although at slower rates than in ecosystems beyond the Front Range with higher average moisture and temperatures (e.g. Stephens et al. 2012, Kreye et al. 2014).

Wildlife Responses

A common objective of many chipping and mastication projects is to reduce tree density and increase shrub and herbaceous vegetation forage for large game mammals. While mastication can be successfully used to target habitat improvement for specific species (e.g. Reemts et al. 2014), there can be unintended consequences for non-game species (Gallo et al. 2017). Untangling the impacts of reducing tree and shrub density from the unique effects of adding mulch is especially difficult in wildlife management. For example, non-game small mammals and birds exhibited a short term response to tree cover removal, but their response did not differ significantly between three different slash management methods in western Colorado (Bombaci et al. 2017). Much remains unknown about specific wildlife taxa or functional group response to mulching. The long-range mobility of many species presents challenges to drawing broad conclusions about direct impacts of chipping and mastication on wildlife abundance and community dynamics. When evaluating wildlife responses to chipping and mastication, it's important to compare species habitat needs with expected management outcomes. Additionally, it is important to consider the impact of mulching activities on the immediate treatment area in the context of potential changes on the larger landscape.

Ecological Impacts of Mulching

- Reducing woody plant density with mulching generally increases resource availability (light, water, nutrients) for shrub and herbaceous plant production.
- Mulch depth and distribution rarely exceed levels that inhibit plant growth and tree regeneration.
    1. Tree regeneration is not negatively impacted by mulching treatments except in localized patches of deep material.
    2. Herbaceous plant abundance is suppressed only locally under deep mulch.
- Generally, soil nitrogen cycling is not significantly altered except where mulch depths are greater than 6 inches (15 cm), which is rare over large areas.
- It likely takes more than 10 years for ecological processes like decomposition to reduce the adverse effects of surface fuel loading and potential fire behavior, especially in drier habitats along the Front Range.

Nutrient Cycling

Nutrient cycling, soil moisture, and total soil nitrogen (N) vary following mastication and chipping, and in some cases these changes are long-lasting. Soil moisture in the initial years after mulching is often higher than untreated areas, likely due to the incorporation of chips into the soil profile, and the reduction in transpiring woody biomass (Massman et al. 2006, Rhoades et al. 2012). Soil moisture is generally elevated year-round under masticated areas as long as mulch is present (10+ years) compared with unmasticated habitats (Battaglia et al. 2010). Soil carbon dioxide can also increase in the first several years after mastication (Massman et al. 2006).

The impact of mulching on available N is strongly dependent on the time since mulching. For example, one study found mulching did not alter N availability in relatively productive soils during the first two years after treatment, but was associated with increased soil N availability in the third growing season (Miller and Seastedt 2009). In another study, available N 3 to 5 years after treatment was 32% higher in mulched areas compared to untreated forests (Rhoades et al. 2012). Generally, soil nitrogen cycling is not significantly altered except where mulch depths are greater than 6 inches (15 cm), which is rare over large areas. Heavy mulch application can temporarily reduce soil N availability in very localized areas, but at common operational applications across Colorado conifer forests mulch treatments tend to increase soil N availability (Rhoades et al. 2012).

Fire behavior, effects, and severity after mulching

Fuels mitigation projects are generally designed to modify potential fire behavior to improve fire suppression opportunities and/or enhance the benefits of fire as an ecosystem process. Mulching fuels reduces tree density by removing crown and/or ladder fuels, but concerns remain about the potential impact of rearranging fuel and adding large amounts of small-sized woody material (less than 1 inch in diameter) to the soil surface. Although woody debris ignites less easily than herbaceous or needle litter fuels, woody fuels combustion produces more energy and burns for longer periods of time (Figure 1). Mulching as a wildfire hazard mitigation treatment often presents tradeoffs when compared to other woody vegetation management methods. The following discussion is intended to inform the design of chipping and mastication treatments to achieve your desired outcome when mulched fuels burn.

Fire Behavior and Effects

Short flame lengths less than ~3ft (~1m) and slow rates of fire spread in mulched fuels are commonly observed under mild burning conditions during prescribed fire situations (Bradley et al. 2006, Glitzenstein et al. 2006, Knapp et al. 2011, Reiner et al. 2009) and controlled experiments (Busse et al. 2010, Kreye et al. 2014, Sikkink et al. 2017). However, fire in mulched fuelbeds often smolders and burns long after the initial fire front has passed. Keane et al. (2017) found that fire often burned around large pieces of masticated fuel, which acted to slow fire spread. The larger fuel then burned and added to smoldering time after the fire front passed. Lyon et al. (2018) also observed long fire duration times during a prescribed fire in some locations where mastication had resulted in high woody fuel loadings mixed in with litter and soil. Woodchips smoldered and burned for a much lon-

What Happens When Mulch Burns?

- Mulching crown fuels often leads to fire burning on the surface rather than through tree crowns, which increases opportunities for suppression to slow fire spread.
- Mulched areas may present unique fire behavior and firefighter safety concerns due to elevated risk of high surface fire intensity and long fire duration. This can test fire containment and complicate fire suppression actions compared to other surface fuel types.
- Mulching often does little to mitigate fire severity or post-fire tree mortality. Especially under severe fire conditions, mulching is likely more effective at changing *fire behavior* than mitigating post-fire *ecological effects*.
- Rearranging fuels via mulching can benefit fire suppression operations and fire effects objectives. However, as the amount of mulch left on site increases, fire suppression effectiveness and post-fire ecological outcomes can be compromised.

Severe Fire Conditions

During extreme fire conditions (dry, hot, windy weather), reduction of tree and shrub canopy can bring crown fire down to the ground, increasing suppression opportunities. However, in severe conditions when suppression resources are often strained, mulch commonly burns longer and produces more heat than other surface fuel types. This can complicate fire management and result in elevated levels of surface fire intensity, soil burn severity, tree scorch, and vegetation mortality.

Moderate Fire Conditions

Mulched fuelbeds can retain more moisture than other surface fuel types, and in less extreme fire conditions (wetter, cooler, low wind), mulch may not even ignite. Under moderate fire conditions, mulched woody biomass can increase burn heterogeneity and ecological benefits resulting from higher soil and fuel moisture. However, when mulched fuels do burn under moderate conditions, there is potential to exacerbate smoldering duration and smoke production.

ger duration (e.g. days to weeks) compared to other woody activity fuels, pine needles, or grass fuel types (e.g. minutes to hours) at a prescribed fire in Boulder County (Ziegler et al. 2014). As with fire in any fuel type, longer burning duration increases opportunity for fire to reignite or produce embers that test containment lines as fuel and weather conditions change. In wildland and prescribed fire situations, increased smoldering and fire duration in mulched fuelbeds is often a significant challenge for fire suppression, containment, and control (Bass et al. 2012, Bradley et al. 2006, Knapp et al. 2011).

While mulching can complicate fire suppression effectiveness, mulching treatments have also facilitated successful fire suppression and control in both wildfire and prescribed fire scenarios. In the example of an Idaho wildfire, Hudak et al. (2011) attributed the change from a crown fire to a surface fire and a slowing of the fire spread rate to a mastication treatment. They speculate that this change in fire behavior in the masticated area potentially aided fire suppression efforts. Despite the addition of mulched surface fuels in some prescribed fire settings, flame lengths and rate of spread have been shown to be similar between masticated and unmasticated sites (Lyon et al. 2018). Depth of mulched fuels alone is not well correlated with flame lengths, and other factors contribute to fire behavior. For example, different weather and burning conditions influence fuel moisture content and fire type (e.g. heading vs. backing) (Jin and Chen 2012, Kreye et al. 2014).

Packing ratios—a measure of the densities of fuels on the soil surface—are commonly higher in mulched than unmulched areas. Compact mulched fuels can impact fire behavior—when mulch is packed tightly it may limit available oxygen during combustion and/or increase burning time (e.g. Kreye et al. 2014). Vegetation that grows up through a mulched fuelbed can ignite easily and carry fire quickly, while a compact layer of woodchips without vegetation regrowth have less oxygen in the fuelbed and burn more slowly with shorter flame lengths (Kreye et al. 2014). Bulk density of masticated fuels varies greatly in different forest types. For example, ponderosa pine-oak dominated forest and Jeffrey pine-white fir forests had nearly half the average bulk density (7.99-8.05 lb ft^3 [3128-129 kg m^3]) of pinyon juniper areas (14.11 lb ft^3 [226 kg m^3]) (Hood and Wu 2006).

A regional study of mulched fuels of various ages found that mulch persists with few changes to chemical or physical properties and is still readily combustible after 10 or more years of natural decomposition (Keane et al. 2018), especially in Rocky Mountain dry

Figure 1. Mulched fuels may burn discontinuously with some areas remaining unburned, while other areas experience long residence times and burn all fuels down to mineral soil. This may lead to greater ecological effects and fire-induced tree mortality, and/or complicate fire supression.

ponderosa pine forest types. However, Kreye et al. (2016) found that the age of masticated fuelbeds does have an effect on flame height and smoldering duration. Older masticated fuelbeds (10 and 16 years old) had shorter flame heights compared to younger (2 and 4-year-old) fuelbeds, but smoldered 50% longer. The presence of a duff layer underneath chipped or masticated fuels increased smoldering duration and surface heating when mulched fuels were burned in a laboratory setting (Sikkink et al. 2017), but higher soil moisture can moderate how much of the heat penetrates the soil (Busse et al. 2005, Busse et al. 2010, Knapp et al. 2011), which minimizes resultant fire effects on soil biota and plant roots. Busse et al. (2010) suggests that soil moisture is much more important than soil texture for heat transfer when masticated fuels burn, with a minimum of roughly 20% soil moisture during burns largely buffering soil temperatures lethal to plant roots. Since chipping causes minimal soil disturbance and existing duff remains intact under the chipped woody fuels, they could be more likely to smolder and burn longer than masticated fuels, which are typically more integrated with soil and existing duff layers.

Few studies have evaluated fire severity in mulched fuels; however, it is likely that fire severity varies with both mulch loading and burning conditions. In addition to soil heating, tree canopy scorch is also a good indicator of whether or not a tree will survive a fire event. Increased surface fuel loads of masticated fuels likely produced the higher scorch heights seen during a controlled broadcast burn in California's Sierra Nevada Mountains (Knapp et al. 2011). Knapp et al. (2011) also found that soil/duff moisture limited soil heating, but mastication created smaller woody fuel particles (e.g. more 1hr and 10hr fuels) that added additional surface fuels and increased scorch height and tree damage compared to fire in non-masticated areas. Ecological impacts from soil heating in mulched fuels may not be as much of a concern when soil and/or duff moisture is higher, but there could be larger impacts on tree survival following wildfires in mulched areas where fuels and soils are typically drier, leading to increased tree scorch, root damage, and tree mortality.

Within the limited number of studies available, mulch from different types of mastication machines does not appear to result in different fire behavior. In a laboratory setting, Heinsch et al. (2018) suggested that different mastication methods can have an impact on fire behavior, although these differences were not statistically significant. Mastication implementation techniques that are within the control of the operator—such as how long wood is chopped by the machine and the resultant size of mulched material, or mixing of wood with soil and/or duff layers—can have major impacts on fire behavior and success in achieving mulching project goals. Chipping machines minimize operator discretion and always produce relatively small, uniform size and shaped mulch that mix less with soil and existing forest floor. Therefore, it is likely chipped areas burn differently than most masticated treatments. Further experimentation and documented cases of fires in mulched areas would help to increase our understanding of the interactions between mulching and fire suppression, and the ecological benefits of fire in mulched areas.

In summary, mulching reduces crown fuel connectivity, but the additional woody surface fuel typically persists and creates elevated potential surface fire risk for many years in Colorado Front Range ecosystems. Moderated flame lengths and increased fire residence time are commonly, but not universally, observed fire behavior traits in chipped and masticated fuels compared to fire behavior in other surface fuel types. All mulching treatment options redistribute fuels and do not remove them, so it is important to consider whether this is the best treatment option when the primary goal is fuel hazard reduction.

Knowledge/research limitations

Certain ecosystem effects are more understood than others, and broadly applying these results across the entire system may not be representative. Furthermore, our understanding of mulching impacts on wildfire behavior and severity is limited. Many of the burning studies to date were either conducted in a burn lab under very controlled conditions, or mulch was burned in a prescribed fire when fire weather conditions were mild. Thus the comparability of fire effects and behavior between a lab burn, prescribed fire, and wildfire is questionable, with studies (Lyon et al. 2018) and meta-analyses (Kreye et al. 2014) demonstrating that burn lab experiments do not adequately predict actual forest prescribed fires. There is strong evidence mulching increases surface fire intensity and duration, but more research on the specifics of how fire burns in mulched fuelbeds is needed, especially for Colorado fuel types. Knowledge about processes like ember production that particularly test containment and are a large source of structure loss would help to inform tradeoffs for rearranging fuels via mulching compared to other fuel reduction practices. Additional research about fire in different kinds of mulch would help to determine what types of treatments are most effective for meeting project objectives when mulch burns.

Mulching guidelines near structures

Colorado State Forest Service defensible space guidelines and other guidance suggest removing as much fuel as possible very close to structures, generally within 100 feet. Therefore, mastication and chipping activities that rearrange fuels but do not remove them are not recommended in the immediate vicinity of structures. As the distance from structures increases beyond 100ft, benefits of redistributing fuels via mulching to reduce crown fire hazard should be weighed with potential increased fire residence time in mulch, which can complicate fire containment and extend the time structures are exposed to fire. Strategies that reduce, rather than rearrange, wildland fuels such as hauling material off site, piling and burning biomass, or carefully applied prescribed fire are alternative fuels mitigation options near structures. Reducing wildland vegetation fuels can aid fire suppression, but using fire resistant building materials and reducing fuel hazard from adjacent structures are critical to increasing chances structures survive fire events. Knowledge about wildfire in wildland urban interface settings is rapidly evolving and guidelines will likely be updated in the future.

Mulching Planning Guidance

The following guidelines provide a framework for natural resource professionals and land managers to use as they plan and design mulching treatments in forests and woodlands of the Colorado Front Range. The guidelines demonstrate the benefits of establishing clear goals and objectives, and including specific metrics beyond average mulch depth. Adaptive management and long-term monitoring will continue to fill knowledge gaps and improve effectiveness of mulching practices.

1. ***Establish goals and objectives***

Establishing clear, specific, measurable goals and objectives is the first step to any successful land management project. When considering whether to mulch woody fuels, first identify specific vegetation management goals and future desired conditions. Next, establish specific and measurable objectives to ensure that management results can be evaluated against desired goals. This process will help determine if vegetation rearrangement via mulching is an appropriate tool, if single or multiple treatments are necessary, or if a combination of management options are best. Longevity of treatments and maintenance of the desired conditions also need to be considered.

Mulching is mostly used to remove small-diameter trees and shrubs; however, it is often ecologically and/or aesthetically desirable to maintain a variety of size and age classes of trees and shrubs on the landscape. Unless specifically desired, use caution so that chipping and mastication activities do not remove all smaller trees in the stand, resulting in even-aged and even-sized stands. Retention of old growth trees (greater than

Table 2. Example resource goals and objectives for ecosystems in the Colorado Front Range

Project Goals and Sites	Goals *What do you want to accomplish?*	Objectives *What actions are needed to accomplish the goals?*
Increase forest resilience to disturbances (fire, insects and disease), while protecting communities and human values at risk *in a low elevation, dry, frequent fire forest or woodland*	Example: Reduce forest density to increase forest resilience to disturbances and reduce potential for large crown fires.	Reduce conifer tree density, raise crown base height, reduce surface fuel loading, retain large fire resistant trees, increase proportion of ponderosa pine to other conifers, increase forest habitat heterogeneity at small and large scales.
Increase forest resilience to disturbances (fire, insects and disease), while protecting communities and human values at risk *in a high elevation, moist, infrequent fire forest or woodland*	Example: Increase tree vigor and resilience to insect and pests outbreaks. Promote aspen tree recruitment.	Reduce conifer tree density, increase aspen regeneration, create multi-aged forests, increase number of small (<1 acre) openings.
Create fuel breaks to aid fire supression efforts	Example: Improve opportunities for fire suppression by reducing the potential for active crown fire.	Reduce and/or remove tree canopy fuels within 200 feet of structures, reduce surface fuels, create discontinuous forest patches, raise crown base height.
Hazard tree removal	Example: Removal of standing dead trees as hazards to human safety, for aesthetics, or green tree removal near utility lines.	Remove 50% of hazard trees in area of interest, remove all trees within 1.5 tree lengths from a road or trail.

200 years old, Huckaby et al. 2003) is important in Front Range forest systems, but it is sometimes necessary to remove some large trees in order to accomplish resource objectives. Because chipping and mastication treatments are generally focused on changing densities of small trees and woody vegetation, mulching is often used as a complimentary tool and rarely as a stand-alone treatment method when larger trees also need to be removed.

Resource Protection - Special Considerations

The nature of mulching requires that managers take special consideration of vulnerable and erodible sites, waterways, and infrastructure before implementing a project. Avoid depositing mulched woody materials into waterways (perennial streams, drainage ditches, and culvert basins) to prevent clogging utility infrastructure. Consider delineation and protection of streamside management zones during project layout and boundary marking. For more information on erosion control, consult the Colorado State Forest Service publication, *Colorado's Best Management Practices for Protecting Water Quality* (CSFS 2010). Identify and map the proximity of existing structures to treatment areas to ensure that woody debris and rocks thrown from the mulching equipment do not damage buildings and other infrastructure.

2. Inventory vegetation based on desired structure and composition

Inventory the current vegetation using the measurements specified by your goals and objectives. Identifying and quantifying the type, quantity, and arrangement of vegetation and fuels in your management area helps to determine the actions you need to take to achieve desired conditions. For example, if your goal is to reduce the probability of crown fire initiation and crown fire spread, then your objectives should establish specifications for reducing tree density, raising crown base heights, increasing spacing between tree canopies, and reducing surface fuel loadings. Typical forest inventories include measurements of tree density, tree size (e.g. diameter at breast height, DBH), surface fuel loadings, shrub type, density, and abundance, and plant species composition, especially noxious weeds.

3. Evaluate mulching as a management option

Assess the consequences of adding woody biomass to the forest floor. Based on the inventory data from the management unit, use Table 3 as a guide to estimate the average loading and depth of woody material that will be rearranged from standing vegetation to the soil surface. It's important to note that averages

Table 3. Surface fuels created by mastication: how much mulch to expect. Data adopted from Battaglia et al. 2010 and applies only to masticated (not chipped) fuel beds.

Tree BA removed Ft2/ac (m^2/ha)	Masticated fuel bed (litter + duff + 1hr + 10hr) Tons/acre (mg/hectare)	Approximate average depth inches (cm)	Table Definitions
22 (5)	5.4 (12.1)	0.4 (0.9)	***Tree BA removed:*** Tree basal area rearranged from the canopy to the soil surface ***Litter:*** pine needles and dead, loose herbaceous vegetation ***Duff:*** partially decomposed organic material above the soil surface ***1hr and 10 hr fuels:*** woody debris of two size classes: 0.01-0.25 inches diameter for 1 hr fuels and 0.26-1 inch diameter for 10 hr fuels.
44 (10)	9.7 (21.8)	0.6 (1.6)	
87 (20)	18.4 (41.3)	1.2 (3.0)	
130 (30)	27 (60.7)	1.7 (4.4)	
174 (40)	35.7 (80.1)	2.3 (5.8)	

across large management areas are often low, and locally deep patches are common. The expected depth and distribution of mulch, as well as residual vegetation and anticipated future vegetation growth, need to be considered when evaluating treatment methods.

Consider the following questions when evaluating mulching:

- Following mulching treatments, is the residual standing vegetation within your identified objectives?
- How will the predicted depth of mulched material impact your management goals? Note that Table 3 provides average depths from basal area reductions. Consider additional guidelines (see table 4) for contractors working in dense vegetation, doghair thickets, or mulching slash to avoid locally deep mulch.
- If further reductions in woody vegetation density are needed to produce the desired forest or shrubland structure, will more mulching still result in an acceptable depth and distribution of woody material on the soil surface?
- If there are concerns about mulch depth negatively impacting resource management goals, can the biomass be moved off site, or safely reduced by prescribed fire or pile burning operations? Is another harvest method needed to complement mulching and reduce mulch depths?
- Are the negative impacts of the mulch outweighed by the benefits of reduced forest and woodland density?

In Colorado Front Range forests, mulching treatments are generally an economical option when management goals include a large area of shrub and/or small tree mitigation (e.g. less than 8 inch diameter at breast height, DBH) (Harrod et al. 2009). As the density and size of trees needing mitigation increases, mulching generally becomes less practical as a forest management tool. Setting hard diameter limits can inhibit the ability of managers to achieve project goals, and sometimes large tree removal is necessary to achieve goals in forest management. If the vegetation inventory indicates that the project objectives require removal of trees generally larger than 8 inches DBH, we recommend using other treatment tools to complement or replace mulching. Complementary or replacement treatments could include whole tree harvesting, prescribed fire, pile burning, or other biomass removal options. However, because project goals vary by site and forest condition, there may be times when converting large amounts of overstory biomass to surface woody biomass can provide positive results. For example, post-fire mulching of large hazard trees adds mulch to the soil surface and could reduce the potential of post-fire erosion in a recreation area. Clearly defined management goals and objectives are your best guide for evaluating treatment options. In any situation, we do NOT recommend setting hard diameter cut limits in your management plans.

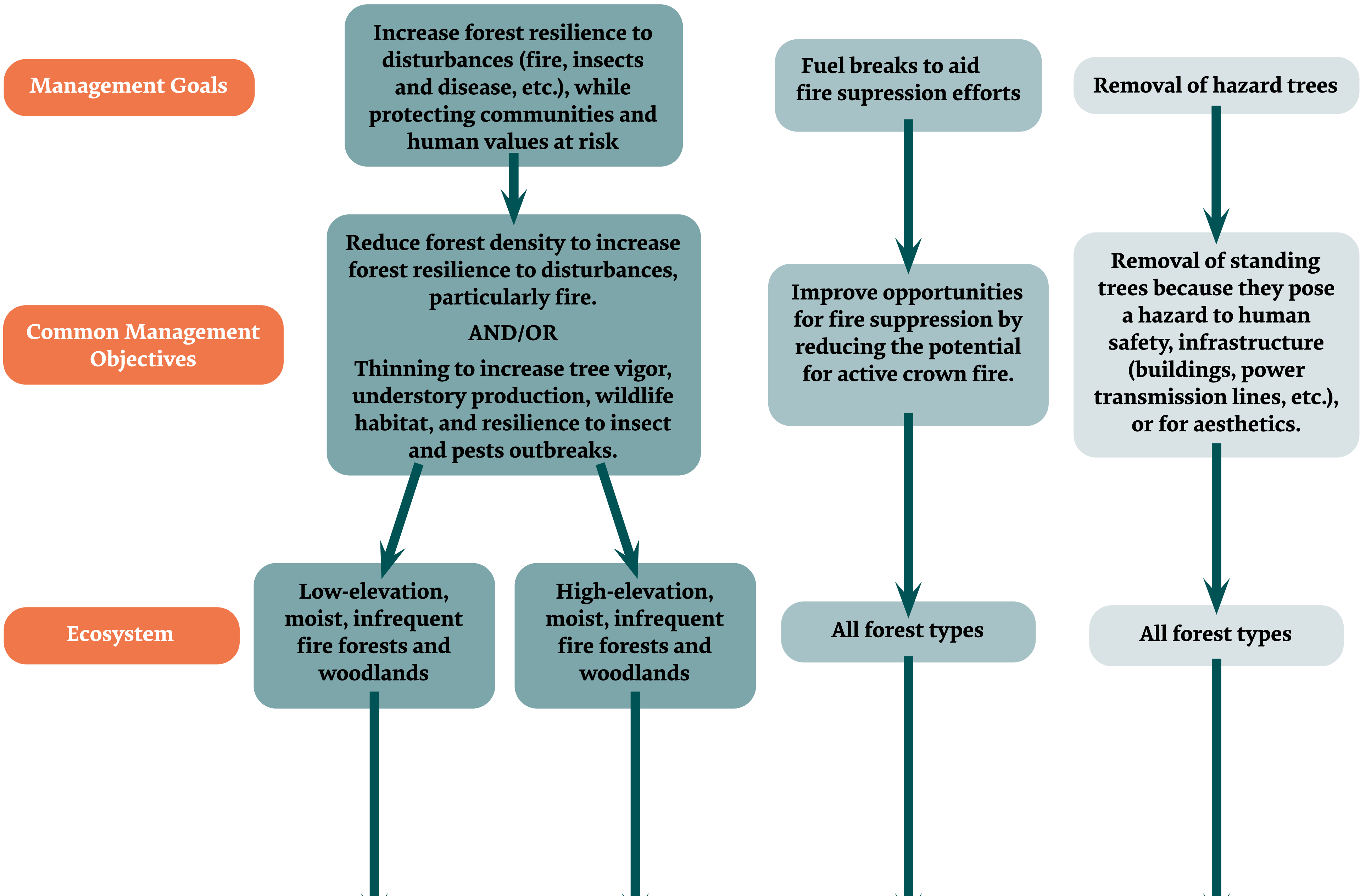
4. *Determine implementation specifications*

Specifications should be based on, and informed by, management goals, specific resource objectives, inventory assessment, special resource considerations, and resource limitations. Setting measurable specifications facilitates clear communication between the project manager, forest planner, contractor, contract administrator, and other interested parties. Clear communication is essential to successful projects and helps avoid undesired outcomes (See table 4 for example specifications).

5. *Develop an adaptable long-term monitoring plan*

Assessments of effectiveness and the expected longevity of initial treatment benefits should follow operations. These assessments will inform long-term planning to maintain treatment benefits and scheduling of future management (See insert on Monitoring for Implementation Compliance).

Table 4. This table describes examples of common management goals and project specifications to consider when designing mulching projects on Colorado's Front Range. This information is intended to guide more detailed project-level planning, and not to prescribe a one-size-fits-all approach. Numbers in this table are meant to complement clear project goals and inventories of local conditions, and do not replace the need to complete these planning steps. Metrics are derived from a combination of scientific research summarized in this document, and expertise from discussions with Front Range Roundtable partners. Some additional guidelines from other regions are provided in the additional resources at the end of this document.



Example Implementation Guidelines Summary	Minimize mulch depth and distribution by mulching small amounts of biomass or using mulching as a complementary management tool. Excessive depths over large areas are typically rare, but can have negative ecological impacts if deep patches of mulch cover large areas. Minimize risk of undesirable surface fire severity and reduced suppression effectiveness by minimizing mulch depth and distribution.	High natural surface fuel loads typically minimize ecological and fire impacts of mulch additions. Due to higher forest productivity, continuous mulch coverage and higher depths are common. Decomposition rates reduce mulch longevity compared to lower elevation or less productive areas. Reducing crown fuels enhamces fire suppression options, but surface fuel additions can limit suppression effectiveness under dry and windy fire conditions.	Deep and continuous mulch can complicate fire containment by increasing burning duration, but mulching is beneficial when these risks are generally outweighed by benefits of crown fuel reduction in key tactical locations. Consider maintenance needs following mulching of re-sprouting species (e.g. aspen, Gambel oak, serviceberry.).	Mulching individual trees can create localized high biomass loads, but generally over a small area and where efficiently protecting life and safety are higher priority even if ecological condition or fire risk reduction objectives are slightly compromised.
1) Distribution of mulch (e.g. *XX–XX%* of the management area will be covered with mulched material).	Discontinuous coverage minimizes ecological impacts and risk of prolonged surface heating and exacerbated severe fire effects; ex: mean percent cover of mulched material not to exceed 40%	Heterogeneous coverage is best to increase biodiversity and ecosystem resilience; ex: mean percent cover of mulched material 40—60%	Minimize accumulation and encourage discontinuous coverage when possible; ex: mean percent cover of mulched material 20—40%	Generally no distribution limit, dependent on individual tree locations.
2) Maximum allowable mulch depth (e.g. woody material shall not exceed *XX* inches within any part of the management area).	Excessive depths have negative ecological implications and minimize fire suppression effectiveness, e.g. 6—8”	Higher depths are expected compared to drier forest types due to high starting biomass levels, e.g. 12”	Minimize deep accumulations, especially near expected containment lines, e.g. 4—8”	Consider aesthetic and fire impacts, otherwise generally not applicable when mulching individual trees
3) Maximum mulch patch size (e.g. continuous mulch cover will not exceed *XX* area).	0.25 acres	1 acre	100 square feet	No patch size limit
4) Maximum size of mulch pieces (e.g. wood pieces will not exceed *XX* diameter and *XX* length).	Generally smaller to increase decomposition and aesthetics, but variable sizes desired, e.g. 2’ long by 3” diameter.	Large chunks and variable sized logs enhance wildlife habitat, e.g. 6’ long by 6” diameter.	Minimize mulch size to facilitate safe fire operations, e.g. 2’ long by 3”diameter	3’ long by 3” diameter to enhance aesthetics.
5) Average mulch depth (e.g. mulch depths will average *XX* inches across the management area).	0.5-1”, minimize to reduce risk of surface fuel loading and potential fire severity	2-3” or less to maximize understory growth and tree regeneration	1-2” to minimize fire residence time and post fire mop up.	Depths greater than 6” suppresses understory vegetation and tree regeneration

Metrics are derived from a combination of scientific research summarized in this document, and expertise from discussions with Front Range Roundtable partners.

Monitoring for Implementation Compliance

Consistent and clear communication of project goals and specifications between the equipment operator, contractor, project administrator, land manager and/or property owner early in the implementation process is essential to project success. Project monitoring helps increase effective communication. Monitoring teams can facilitate common understanding to discuss whether goals are being met and if modifications to the scope of work are needed. Site inventories should be done at repeated intervals: before operations begin, during active operations early in the mulching process, and upon project completion. Below are some general monitoring guidelines you might use to assess whether or not the contractor is meeting project specifications described in Table 4.

Suggested Monitoring Protocol

1) ***Distribution of Mulch:*** To assess mulch distribution and coverage, establish a randomly located transect within the treatment area. The transect should be long enough to sufficiently capture the patchiness of the mulched material (at least 100 feet). To accurately assess the average distribution of mulch throughout the treatment area, random placement of the transect is important. At regular points along the transect (e.g. every 1 foot, every 3 steps, etc.), record the type and depth of material encountered on the forest floor (e.g. mulched biomass, non-mulched biomass, litter, duff, bare soil, rock, etc.). To calculate the average distribution and cover of mulch, sum the number of times mulched material was encountered along the transect and divide by the total number of measurements along the transect. Multiple transects (at least 3) are recommend to assess any site, with more transects for assessing larger areas or if more precision is desired.

2) ***Maximum Mulch Depth:*** Unlike #1, sampling should be targeted and not random. Survey and locate areas where mulch appears thick and take several depth measurements, recording the maximum depth located. Ranges of mulch depths are inherent in chipping and mastication operations, but targeted monitoring for excessively deep and continuous accumulations of mulched woody biomass can mitigate undesirable outcomes.

3) ***Maximum Mulch Patch Size:*** If large patches of masticated material are undesirable and observed during treatment operations, target the largest patches and measure their area. To characterize large patches, measure the depths of material along a transect to determine mulch continuity and average depth within the patch area. Large areas with heavy, continuous woody debris should generally be minimized to accomplish most common mulching management objectives.

4) ***Maximum Size of Mulch Pieces:*** Survey the masticated area and measure the dimensions of large woody debris that appear to exceed specifications. Implementation directions should have specified if all woody material (downed and standing) was to be mulched to meet size limits, or if a variety of sized materials were desired. Finer mulch may be desired to increase decomposition rates or for aesthetics, while larger pieces or a variety of sizes may be desired to reduce fine fuels that contribute to fire spread rates, or to provide specific wildlife habitat structure.

5) ***Average mulch depth:*** Average the depth measurements of mulch measured along the transect described in #1. For average depth of all fuels at the site, include all measurements where mulch and unmulched fuels are present in the average. This is the most common monitoring method. To determine the specific depth of mulched fuels at a site, include only mulch depth measurements in your calculations.

Distribution of Mulch is as Important as Depth

Managing Debris Distribution

Make an effort to reduce the number of areas within treatment units where there is heavy accumulation of woody material. Creating an uneven distribution of woody debris is important to allow for plant regeneration, soil health, and discontinuous surface fuels.

- Chippers offer some ability to control debris distribution by manipulating the direction and coverage of chips. Additionally, chipping into piles or receptacles facilitates removal of material from the project area.
- Masticator operators often have limited ability to control the distribution of wood on the soil surface, but where topography allows operators can approach standing vegetation from different directions. Approaching trees or brush from varying directions can alter where material is projected onto the soil by as much as several hundred feet, and create a patchwork of heavier and lighter accumulations of masticated material.
- Mastication equipment can be modified with shields and other apparatus to improve operator ability to control the distribution of masticated material. Boom mounted masticators add additional discretion in directing masticated biomass.

Managing Debris Depth

Specifying sizes for trees or brush to mulch (e.g. diameter, height, clump size, and distribution), or the size of clumps or groups of vegetation to retain can manage the depth of mulch debris. If less mulched material is desired on the soil, treatment options that remove biomass from the site, such as whole tree harvest or chipping into roll-off dumpsters, are recommended as a complementary management tool. Actual depth of mulched material on the forest floor can vary greatly across a treatment area. For example, in Colorado depths often average only 0.5 to 2-inches in most areas, with localized pockets of heavier accumulations (Battaglia et al. 2010).

Even and heavily distributed chips. In larger masticated treatment areas in Colorado (several acres or more), average coverage of woody material is about 60% (Battaglia et. al, 2010). However, any given square foot within a treatment area may be fully covered in masticated material or have none at all.

In Colorado, average mulch depth is 0.5 to 2-inches.

Localized pockets of heavier accumulation

Suggested Readings and Resources

Many additional resources are available to inform mulching practices. Here are just a few we find especially useful.

- The Southern Rockies Fire Science Network fuel treatment information website maintains an updated summary of mulching information (http://www.southernrockiesfirescience.org/activity-fuels).
- *Firefighter perspectives on prescribed fire in chipped areas: Barriers and Benefits: The Wapiti Prescribed Burn Fire.* Video produced by the Southern Rockies Fire Science Network. (https://youtu.be/RtuaZef-ido)
- *Mulching the Forest: Putting Science to Action.* Presentation of content in this document at the 2018 Colorado Wildfire Conference, Crested Butte, Colorado. (https://youtu.be/Mmcq-9vd7yI).
- *Forestry Best Management Practices to Protect Water Quality in Colorado.* Colorado State Forest Service, Fort Collins, CO, 2010. (http://static.colostate.edu/client-files/csfs/pdfs/ForestryBMP-CO-2010.pdf)
- *To masticate or not: useful tips for treating forest, woodland, and shrubland vegetation.* USDA Forest Service General Technical Report RMRS-GTR-381. (https://www.fs.fed.us/rm/pubs_series/rmrs/gtr/rmrs_gtr381.pdf).
- *Mastication Fuel Treatments in the Southwest.* Summary document produced by the Southwest Fire Science Consortium. (http://swfireconsortium.org/wp-content/uploads/2013/01/mastication_final.pdf).
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