Graham, Russell T.; McCaffrey, Sarah; Jain, Theresa B. (tech. eds.) 2004. **Science basis for changing forest structure to modify wildfire behavior and severity.** Gen. Tech. Rep. RMRS-GTR-120.

Introduction from FWRI:

This document is a synopsis of a much longer report, and is a doorway to state-of-the art knowledge on the topics of forest structure, wildfire behavior, and their relation to one another. This synopsis was prepared for someone in the Southwest, and particularly in New Mexico, that has neither the time nor the inclination to wade through a longer document. However, the original is so good that it deserves a wide audience, and we hope that this synopsis will lead the reader to the original. We especially urge interested land managers to make an effort to read the original, for we feel they will benefit from it.

We emphasize that this is not our work, but that of the editors and researchers of the research arm of the USDA- Forest Service. In most cases, sentences were lifted verbatim from the report, and the language is that of the original. We accept responsibility for the inadvertent errors we caused.

As its title indicates, the original report is a scholarly work, with conclusions either a consensus of the large group of scientists that contributed to the report, or attributed to the original authors by citing the literature. One way to reduce a 43-page literature review to only seven pages is to leave out the literature citations, and that is what was done here. This is another reason to seek out the original, because many answers can be found in the literature cited. The original is also illustrated with drawings, graphs, and photos.

The original document is online at www.fed.fed.us/rm/publications/titles/rmrs_gtr.html. *It is 2.8 megabytes. Hard copies may also be available from the USDA-Forest Service Rocky Mountain Research Station or other outlets.*

Selected Key Points

• Models, field observations, and experiments indicate that for a given set of weather conditions, fire behavior is strongly influenced by fuel structure and composition.

• Crown fires are dependent on the sequence of available fuels starting from the ground surface to the canopy. Crown fires are more likely to occur when sufficient surface fuels are available to ignite ladder fuels and/or the lower crowns of overstory trees.

• Reducing the likelihood of crown fires requires decreasing the amount, density, and continuity of surface fuels, and removing ladder fuels.

• Surface and ground fires especially those with long (hours to days) residence times can destroy soil organic matter, reduce forest productivity, and on some settings fuse soil particles that in turn can dramatically increase soil erosion compared to unburned sites.

• In forests that have not experienced fire for many decades, multiple fuel treatments—that is, thinning and surface fuel reduction—may be required to significantly affect crown fire and surface fire hazard.

• Models and observations of landscape scale fire behavior and the impacts of fuel treatments clearly suggest that a landscape approach is more likely to have significant overall impacts on fire spread, intensity, perimeters, and suppression capability than an approach that treats individual stands in isolation.

Two definitions:

- wildfire **intensity** - the rate at which a fire is producing thermal energy in the fuel-climate environment, most often measured in terms of temperature and heat yield.
- wildfire **severity** - the effect the fire has on vegetation, soils, buildings, watersheds, and so forth; most often expressed in terms of the post-wildfire condition of litter, soil, trees, etc.

Introduction

Physical setting, weather, and fuel combine to determine wildfire intensity and severity. Of these three factors, fuel (vegetation) is the only one that can be treated.

Fire exclusion through fire suppression or reduction of fine fuels through grazing, urbanization, and other land use changes, particularly in the dry ponderosa pine and Douglas-fir forests, caused a dramatic reduction in the area burned by frequent fires. In turn, these and other past management activities resulted in significant changes since the late 1800s in the structure of forest stands. Most likely, the greatest changes in stand structure from those occurring historically, occurred on productive sites where vegetation readily developed.

Prior to the 20th century, low intensity fires controlled regeneration of fire-intolerant (plants unable to physiologically withstand heat produced by fires) species, promoted fire-tolerant species (for example, ponderosa pine and Douglas-fir), maintained an open forest structure, reduced forest biomass, decreased the impacts of insects and diseases, and maintained wildlife habitats for many species that utilize open stand structures (for example, northern goshawk). In addition to the accumulation of fire intolerant vegetation, dense forest canopies with homogeneous and continuous horizontal and vertical stand structures (for example, dense trees with low crown base heights) developed, resulting in an increased potential for crown fires in many forests of the Western United States. These changes in structure and composition have dramatically altered how wildfires now burn in these forests from how they burned historically.

The greatest changes in ponderosa pine and dry Douglas-fir forests have occurred predominantly in fire regimes characterized historically by high frequency surface fires. Dry forests historically contained diverse understories most often of grasses, forbs, and low shrubs—a condition maintained by frequent, low-intensity surface fires.

Fuels - Fire behavior and severity depend on the properties of the various fuel (live and dead vegetation and detritus) strata and the continuity of those fuel strata horizontally and vertically. Understanding the structure of fuelbeds and their role in the initiation and propagation of fire is the key to developing effective fuel management strategies.

Fuelbeds are classified in six strata: (1) tree canopy, (2) shrubs/small trees, (3) low vegetation, (4) woody fuels, (5) moss, lichens, and litter, and (6) ground fuels (duff). Each of these strata can be divided into separate categories based on physiognomic characteristics and relative abundance. Modification of any fuel stratum has implications for fire behavior, fire suppression, and fire severity. For instance, woody fuels and ground fuels are most often associated with smoldering fires and residual combustion that can transfer large amounts of heat deep into the soil. Using prescribed fire or mechanical methods to reduce the amount, depth, and continuity of surface fuels left after forest management activities, especially those fuels less than 3 inches in diameter, reduces the likelihood that overstory canopies will ignite during a wildfire.

Fire behavior –

In general, wildfire behavior is influenced by short- and long-term weather, physical setting (local to regional topography and terrain features), and fuels (composition, structure, moisture content of dead and live vegetation and detritus). All of these elements work in concert over multiple spatial and temporal scales to determine how wildfires behave. Because of the infinite number of combinations of these elements, as well as ignition location, the growth and behavior of each fire are likely to be unique. Fire behavior is typically described at the stand level, but the spatial arrangement of stands affects the growth of large fires across landscapes. Fire behavior characteristics include rate of spread, intensity, residence time, transition to crown fire, and spotting, and are associated with a flaming front. In many fires, fuel consumption and smoke production occur in both flaming and smoldering postflaming phases of combustion, with most consumption of, and smoke production from, woody fuel and ground fuel strata occurring after flaming has ceased.

Fires are usually placed into three broad classes, each containing unique fire behavior characteristics. These fires include smoldering or ground fires, surface fires, and crown fires. *Ground fires*, or residual smoldering fires, are an important but often overlooked component of most fires. The intensity and duration of *surface fires* depend on the availability and condition of surface fuels. Three fuelbed strata (low vegetation, woody fuel, and moss, lichen, and litter) contribute to the initiation and spread of surface fires. The spatial continuity and density of tree canopies in combination with wind and physical setting provide the conditions required for rapidly moving fires that typically consume the crowns (needles and small branches) of large forest areas. Canopy base height, canopy bulk density, and canopy continuity are key characteristics of forest structure that affect the initiation and propagation of *crown fire*. Canopy bulk density (canopy weight for a given volume) varies considerably within stands, but thinning to reduce canopy bulk density to about one-quarter of maximum is generally recommended to minimize crown fire hazard. Below one-quarter of maximum, active crown fire is difficult to achieve.

The relation forest structure has with fire intensity depends on the setting at which the fire occurs, and on weather. Elevation, slope angle, aspect, and physiographic position influence how a fire behaves. Weather and physical setting sometimes control fire behavior, with forest structure having minimal effect. The interaction between weather, physical setting, and fuels will vary depending on the type of fire (crown, surface, or smoldering). Simulations using the computer models BEHAVE (surface fire) and Fire Behavior Prediction (FBP) (crown fire) also indicate that the relative influence of weather and fuels varies as a function of the specific biophysical conditions.

The Hayman Fire in Colorado provides a good example of how the combination of factors (weather, forest structure, physical setting) occurring at multiple spatial scales influence how a wildfire burns. Under those burning conditions, fine-scale forest structural variability (for example, stand density and composition) that may have altered fire behavior under more benign weather had little effect on fire progression. Islands of stands where fuels had been modified were often surrounded by large extents of forest with heavy ladder fuels and high crown densities. As a result, while the Hayman Fire behavior and severity were affected locally, these fuel modifications did little to influence the overall behavior and severity of the fire.

Fire severity and fire effects –

Crown fires remove much of the entire tree canopy in a particular area, with the largest immediate and long-term ecological effects and the greatest potential to threaten human settlements near wildland areas. Surface fires have the important effect of reducing low vegetation and woody, moss, lichens, and litter strata. Ground fires reduce the accumulation of organic matter and carbon storage and contribute to smoke production during active fires and long after flaming combustion has ended. These fires can also damage and kill large trees by killing their roots and the lower stem cambium.

Fuel modifications –

Classically, the term "thinning" was applied to stand treatments aimed at redistributing growth on remaining stems, but often any kind of partial cutting was termed thinning. In all cases these treatments reduce the numbers of stems in a forest stand and can create an infinite number of stand structures. These kinds of treatments can be applied to alter forest species composition and structure to meet management objectives such as producing forage for both wildlife and livestock, producing timber products, creating disease and insect resistant stands, or altering fire behavior and/or severity.

Qualitative observations, limited empirical data, and modeling provide the scientific basis for identifying how forest structure can be modified to reduce fire hazard and modify fire behavior. Additionally, research shows that when activities reduce surface fuels (low vegetation, woody fuel, shrub layer), those activities decrease the chances that surface fires will be able to ignite ladder fuels and canopy fuels. The most effective strategy for reducing crown fire occurrence and severity is to:

(1) reduce surface fuels,
(2) increase height to live crown,
(3) reduce canopy bulk density, and
(4) reduce continuity of the forest canopy

Prescribed fire – Post-treatment stand structure generally is less predictable following prescribed fire than it is with mechanical thinning treatments, regardless of the targeted condition and burning prescriptions, because prescribed fire is not as precise a tool for modifying stand structure and composition. On balance, prescribed fire is a useful tool that can effectively alter potential fire behavior by influencing multiple fuelbed characteristics, including:

• Reducing loading of fine fuels, duff, large woody fuels, rotten material, shrubs, and other live surface fuels, which together with compactness and continuity change the fuel energy stored on the site and potential spread rate and intensity.

• Reducing horizontal fuel continuity (shrub, low vegetation, woody fuel strata), which disrupts growth of surface fires, limits buildup of intensity, and reduces spot fire ignition probability.

• Increasing compactness of surface fuel components, which retards combustion rates.

Mechanical thinning - Mechanical thinning has the ability to more precisely create targeted stand structure than does prescribed fire. Used alone, mechanical thinning, especially emphasizing the smaller trees and shrubs, can be effective in reducing the vertical fuel continuity that fosters initiation of crown fires. In addition, thinning of small material and pruning branches are more precise methods than prescribed fire for targeting ladder fuels and specific fuel components in the ladder-fuel stratum. By itself, however, mechanical thinning with machinery does little to beneficially affect surface fuels with the exception of possibly compacting, crushing, or masticating it during the thinning process. Depending on how it is accomplished, mechanical thinning may add to surface fuels (and increase surface fire intensity) unless the fine fuels that result from the thinning are removed from the stand or otherwise treated.

Mastication, mulching, etc - Additional treatments utilize machines to rearrange, compact, or otherwise change fire hazard without reducing fuel loads. In general, these treatments are limited to relatively gentle slopes and areas of high values near homes and communities. The ecological effects of these treatments vary depending on the size, composition, and location of the fuels left by these techniques. Any of these crushing, chipping, or mulching treatments need to consider their impacts on decomposition processes and their potential contribution to smoldering fires.

Thinning and prescribed fire combined - The most effective and appropriate sequence of fuel treatments depends on the amount of surface fuel present; the density of understory and mid-canopy trees; long-term potential effects of fuel treatments on vegetation, soils, and wildlife; and short-term potential effects on smoke production. In forests that have not experienced fire for many decades, multiple fuel treatments are often required to achieve the desired fuel conditions. Thinning followed by prescribed burning reduces canopy, ladder, and surface fuels, thereby providing maximum protection from severe fires in the future. Potential fire intensity and/or severity in thinned stands are significantly reduced only if thinnings are accompanied by reducing the surface fuels created from the thinning operations.

The most appropriate fuel treatment strategy is often thinning (removing ladder fuels and decreasing tree crown density) followed by prescribed fire, piling and burning of fuels, or other mechanical treatments that reduce surface fuel amounts. This approach reduces canopy, ladder, and surface fuels, thereby reducing both the intensity and severity of potential wildfires. Mechanical treatment to manipulate fuels, used in combination with subsequent prescribed fire, offers a viable alternative, but only where operation of machinery is feasible. For practical reasons, some areas can only be treated with prescribed fire or manual operations using chainsaws, even though the preferred prescription would involve mechanical methods as well. Restoring dry forests to a condition in which fire can be used to maintain the desired conditions will take time. Wildland fire use (that is, allowing certain wildfires to burn under certain conditions and locations) offers some hope once homes and communities and key resources are protected through thinning, prescribed fires, or other treatments.

Post-treatment - All fuel strata need to be managed (over time and space) to minimize the unwanted consequences of wildfires. Thinned stands allow incoming solar radiation to penetrate to the forest floor, which then increases surface temperatures, decreases fine fuel moisture, and decreases relative humidity compared to unthinned stands—conditions that can increase surface intensity. An increase in surface fire intensity may increase the likelihood that overstory tree crowns may ignite. Therefore, the gap between the surface and crown fuels must be maintained through either prescribed fire or pruning so that if a fire should occur, the potential for crown fire initiation is minimized. Changing crown structure while ignoring surface fuels will only affect the likelihood of active crown fires; it will not necessarily reduce the likelihood of surface fires severe enough to damage soils or intense enough to ignite tree crowns.

Even with uncertainties and arguments as to the precision and accuracy of the estimated number of acres (somewhere between 66 million and 100 million) that need to be treated, they clearly illustrate that treatment needs for modifying fire behavior and severity are staggering. Access and operability issues further limit the options available on a large portion of Western forests, and costs and lack of industrial infrastructure to utilize small diameter material are other critical factors influencing treatment possibilities.

Treatment longevity - Few specific experiments have evaluated the longevity of treatments and their effectiveness in altering fire behavior. However, considerable information exists on forest growth and development, and this information can provide estimates of treatment longevity. Studies have shown that the effectiveness of prescribed fire treatments in maintaining desired fuel conditions decreased significantly over two decades in a ponderosa pine forest. Researchers have concluded that prescribed burning in Yosemite National Park would be required at least every 11 years to maintain fuel loads below their preburn condition.

Fuel treatments on large landscapes – The spatial patterns of fuel treatments in landscapes will most likely determine their effectiveness in modifying wildfire behavior, because multiple stands and fuel conditions are involved in large fires. Treating small or isolated stands without assessing the broader landscape will most likely be ineffective in reducing wildfire extent and severity. Given current fuel accumulations across the interior West, small areas favoring low intensity or severity fires will probably be irrelevant to fire behavior. Therefore, treatments that alter vegetation to favor low-intensity or less severe fires must consider spatial arrangement of fuel structures to effectively alter wildfire behavior.

Strategic area treatments create landscape fuel patterns that collectively slow fire growth and modify behavior while minimizing the amount of treated area required. The arrangement of vegetation pattern changes fire behavior by forcing the fire to repeatedly flank around patches of treated fuels. Thus, the rate of growth of the fire is slowed, and its intensity and severity are reduced. The importance of spatial pattern is emphasized by findings that random fuel treatment arrangements are extremely inefficient in changing fire behavior—requiring perhaps 50 to 60 percent of the area to be treated compared to 20 percent in a strategic fashion.

Variability in weather, physical setting, and forest fuels make it difficult to draw general conclusions about the effects of thinning forests to alter fire behavior. A key point is that thinning treatments that are followed by reduction of surface fuels can significantly limit fire spread under wildfire conditions.

Evaluation Tools –

The following is a partial list of common computer models and how they might be used to evaluate the efficacy of thinning for fuel treatments.

- Thinning treatments affecting stand density, height to live crown, and canopy bulk density can be linked to National Fire Danger Rating System (NFDRS) fuel models to evaluate the likelihood of crown fire following fuel treatments.

- Fuelbed Characteristics Classification System (FCCS) estimates quantitative fuel characteristics and probable fire parameters from comprehensive or partial stand inventory data.
- FARSITE is the primary tool used to estimate fire spread, including crown fire, for forest landscapes. This simulation approach integrates geospatial fuels data, climatic data, and fire behavior modeling (BEHAVE) to predict fire spread, but it is difficult to link this approach with straightforward fuel treatment guidelines.
- SIMPPLE (Simulating Pattern and Process at Landscape Scales) can recreate representations of historical conditions for comparison to current conditions of specific landscapes to determine treatment priorities and treatment locations.
- Site-specific activities can readily be evaluated using the Forest Vegetation Simulator (FVS) and the Fuel and Fire Effects extension of FVS to quantify vegetation and fuel succession following fire or fuel treatments.

Uncertainties in predicting fire behavior –

Fire behavior and severity can be understood and predicted in general terms, but exact predictions are not possible. Different models have been developed that are widely used and useful to assist in managing fires and developing fuel treatment plans, but key uncertainties exist. Limitations to predictions using models can be categorized as:

- Model assumptions and indications.
- Unknowable fire environment at the time wildfires encounter treatments.
- Coarse data descriptions of fuels and environmental conditions.
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A key area of uncertainty is in how to determine thresholds of treatment for different fuels when they are encountered by wildfire. In general, models are effective in showing the contributions to the fire hazard made by surface, ladder, and crown fuels; however, each stratum affects fire behavior differently, and no one knows how much treatment is needed in each stratum to achieve desired results.

Stand structure and wildfire behavior are clearly linked, so fuel reduction treatments are a logical solution to reducing extreme fire behavior. However, a majority of the evidence supporting the effectiveness of fuel treatments for reducing crown fire hazard is based on informal observations, nonsystematic inquiry, and simulation modeling. Ongoing studies are continually adding to our limited empirical knowledge on the relation between forest structure and fire behavior.