Desirable Forest Structures for a Restored Front Range

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Front cover: The view looking across a ponderosa pine dominated landscape near Red Feather, CO. This landscape currently has a dense canopy that is only broken up by very steep rocky outcrops and cliff faces (Credit: Yvette Dickinson).

1.0 Introduction

As part of the federal Collaborative Forest Landscape Restoration Program administered by the US Forest Service, the Colorado Front Range Collaborative Forest Landscape Restoration Project (FR-CFLRP, a collaborative effort of the Front Range Roundtable[1] and the US Forest Service) is required to define desired conditions for lower montane ponderosa pine (*Pinus ponderosa*) forests on Colorado's Front Range (approximately 6,000 to 8,000 ft asl) and monitor progress towards these desired conditions. Currently, more than 70% of these forests exhibit high to very high degree of departure from their historical range of variability (FRRT 2009) and the FR-CFLRP aims to "return Front Range ponderosa pine forests to a condition that reduces the threat of uncharacteristic fire; increases forest resilience to fire, insects, disease, drought, and climate change; and provides sustainable vegetation and watershed conditions, wildlife habitat, and community needs" (FRRT 2009). This will be achieved in part by working to "establish a complex mosaic of forest density, size and age" at the stand and landscape scales (Clement and Brown 2011). The following report is a summary of the Front Range Roundtable's efforts to refine these desired conditions for forest structure across the Front Range at both the stand and landscape scales.

Defining the desired condition of forest structure across the Front Range landscape has been difficult. Earlier efforts attempted to define the historic range of variability by collating information from published and unpublished sources through literature reviews and expert interviews; however, the information was often conflicting or lacked robust region-specific detail. In particular, there was a lack of information describing the historic forest spatial patterns that influenced a number of ecosystem processes on the Front Range. Further complicating the process, these ecosystems were historically, and remain today, dynamic ecosystems. Thus, it is important that forest management strategies allow for temporal as well as spatial variation. Therefore, rather than simply describing a static ideal condition, the desired conditions need to reflect the range of forest structures that are appropriate to the socio-ecological context, while grasping the realities of future uncertainties such as global change.

Over the last two years, members of the Front Range Roundtable's Spatial Heterogeneity Subgroup have been engaged in a process to refine the desired conditions of forest structure across the Front Range landscape based on the ecological scientific literature, and the group's values, knowledge and experience. This document is the final outcome of that process, and describes both the process we followed and the best current understanding of desired conditions of forest structure for Colorado's Front Range.

While we rely on the best available science, this document is not intended to be an exhaustive review of the literature. In addition, the desired conditions developed here are largely based on expert opinion due to the limited number of rigorous scientific studies specific to the Front Range. Therefore, the identified desired conditions include considerable uncertainty and should be viewed as preliminary. Furthermore, this document should be regularly revised under the Landscape Restoration team's adopted adaptive management framework using emerging scientific knowledge.

Lastly, in addition to defining the desired conditions, the FR-CFLRP is required to monitor forest restoration treatments for progress towards these desired conditions. The monitoring of these treatments will inform the adaptive management of these forests. Therefore, this document attempts to tie these desired conditions to the FR-CFLRP's monitoring work, and describe the expected changes resulting from successful restoration treatments that may be measured using current monitoring techniques (Clement and Brown 2011, Pelz and Dickinson 2014).

1.1 The process

The members of the Front Range Roundtable Spatial Heterogeneity Subgroup met several times over the course of the last two years to discuss and synthesize these desired conditions following the six-steps described below. While it would be preferable to follow these steps in sequential order, our group discussions were not necessarily as systematic.

1. As the focus of restoration on spatial patterns is relatively new to forest management, as a group we struggled initially to find common language to discuss these facets of the desired conditions. Furthermore, patterns across scales can be difficult to envision and

[1]http://frontrangeroundtable.org

communicate. Therefore we spent some time at the outset of this process discussing and defining the terminology and scales we would use (see 2.0).

2. After defining our scales of interest and terminology, we discussed the likely drivers behind forest structure patterns, and their likely consequences. We reviewed the published scientific literature relating to stand- and landscape-scale forest structure patterns in fire dominated forest ecosystems across the western United States. While there is little information of specific spatial and temporal forest patterns across Colorado's Front Range, studies from other forest ecosystems may provide some generalizations. The outcomes from each study were carefully evaluated in the context of the Front Range, as ecosystems outside this region are likely to be somewhat different (see 3.1, 3.2, 4.1 and 4.2).

3. In addition to describing the likely drivers and consequences of these patterns, as a group we described the undesirable current or future conditions at each of the two scales. Earlier work highlighted that there was a great diversity of opinions among the group and, at times, a lack of common ground. By focusing on the undesirable conditions, the group was able to find some agreement to work from. These undesired conditions provide the "bookends", between which a range of potentially desirable conditions exist (see 3.3 and 4.3).

4. Finally, after discussing the likely drivers and consequences, and undesired conditions, we used this information to inform our description of the desired conditions for the Front Range lower montane forests at the stand- and landscape-scales (see 3.4 and 4.4). During the course of our discussions, several considerations for desired conditions at the regional scale were also raised (see 5.0).

2.0 Some definitions

Group – more than one tree with interlocking crowns, or crowns that potentially will interlock when the trees are mature. In practice this is interpreted as any number of trees within 20 ft of each other (bole to bole).

Landscape – visible features of an area of land that includes both its physical and biological elements (Puettmann et al. 2009); or, a spatial mosaic of several ecosystems, landforms, and plant communities across a defined area irrespective of ownership or other artificial boundaries, and repeated in similar form throughout (SAF 1998).

Landscape-scale – a scale in the order of 10,000-100,000 acres; however, for the purposes of monitoring the boundaries of a landscape are defined by the extent of the surrounding 6th level Hydrologic Unit Code watersheds (12 digit-HUC; USGS and NRCS 2013).

Opening (or gap) – an area within a stand without tree cover that is greater than 20 ft from the bole of any tree. In practice the delineation of openings is subjective, and they are usually delineated by the absence of tree groups or single-isolated trees.

Patch – contiguous area within a landscape of sufficiently homogeneous patterns of vegetation in terms of species composition, basal area or canopy cover, forest structure and fine-scale vegetation patterns (including openings, single isolated trees, groups of trees, or some mixture). While all of these factors are important when delineating patches, they may need to be simplified for monitoring purposes due to limitations in the available remote sensing methods.

Single isolated tree – any tree whose crown does not interlock or potentially interlock with neighboring trees. In practice this is interpreted as any tree greater than 20 ft from any other tree (bole to bole).

Stand – a contiguous group of trees sufficiently uniform in age-class distribution, composition, and structure, and growing on a site of sufficiently uniform quality, to be a distinguishable unit (SAF 1998).

Stand-scale – a scale in the order of 1-100+ acres.

Tree – any woody vegetation with one to a few dominant stems that is, or could potentially be, > 4.5 ft tall.

3.0 Forest structure patterns at the stand scale

Fine-scale patterns of forest structure within the stand-scale are increasingly important in restoration treatments of western dry forest types. These fine-scale patterns are composed of single isolated trees, groups of trees, openings or some mixture that cumulatively form a forest stand (Figure 1). While traditional fuels reduction treatments focused on creating homogeneous forest structures with low amounts and reduced connectivity of fuels, there has recently been a move towards more heterogeneous treatments to restore historical conditions. The following describes likely drivers of these fine-scale patterns, the likely consequences of patterns, undesirable conditions, and our desired conditions for restoration.

3.1 Likely drivers of stand-scale forest structure

There are a number of ecosystem processes that may drive fine-scale spatial patterns of trees at the stand-scale. While there are few published studies that have specifically investigated these processes in the Front Range, it is likely that a combination of processes found in other ecosystems influence the stand-scale structure of Front Range lower montane forests.

One of the primary drivers of heterogeneity is the underlying variability of the resources available for regenerating trees to exploit. Even small variations in topography (elevation and aspect), landform (e.g., swales, ridgelines and toe slopes) and geology can lead to variation in soil development and microclimate, and therefore, the availability of water, soil nutrients and light. This in turn creates variation in plant community composition, regeneration and survival rates. The presence of coarse wood and other biological legacies may also influence the availability of water, soil nutrients and light (Roccaforte et al. 2012). Furthermore, there may be uneven seed dispersal, germination and survival rates due to other processes in addition to variations in resource availability. For example, seed caching by small mammals and birds may lead to patchy seed dispersal (Vander Wall 1993, Briggs et al. 2009, Lorenz et al. 2011). Overtopping shrubs and overstory trees may heterogeneously facilitate (by mitigating extreme environments that may lead to desiccation) or suppress (by shading or desiccating seedlings) regeneration (North et al. 2004, Dyer et al. 2008, Keyes et al. 2009, Sánchez Meador et al. 2009). Also, it has also been suggested that grazing animals may preferentially remove herbaceous competitors and therefore increase the opportunity for woody regeneration in areas that are grazed (Weaver 1950, Cooper 1960, Larson and Churchill 2012). Lastly, tree mortality due to partial disturbances such as insects and disease (e.g. mountain pine beetle) is likely to be patchy, resulting in heterogeneous fine-scale patterns.

Figure 1.

Ponderosa pine stand near Manitou Experimental Forest, Pike National Forest. Note the presence of groups of trees and openings. At the stand scale, fine-scale patterns of trees within the stand are of interest. (Credit: Yvette Dickinson)

Much work investigating fine-scale spatial patterns of trees at the stand scale has been undertaken in the fire-frequent forests of the western U.S. dominated by low- and moderate-severity fire regimes (Larson and Churchill 2012). While historically open ponderosa woodlands of the Front Range at low elevations (less than approximately 7,000 ft asl) had frequent low severity fire regimes, much of the Front Range's lower montane forests exhibited a mixed severity fire regime with a patchwork mosaic of low- and high-severity fire (Veblen et al. 2000, Sheriff and Veblen 2006). However, despite these differences in fire regime, it is likely that ecological processes similar to those described by Larson and Churchill (2012) also occurred on the Front Range.

Larson and Churchill (2012) proposed a process of "safe-sites" for regeneration leading to heterogeneous tree distributions in ponderosa pine-dominated low and moderate-severity frequent-fire regime forests. Through this process, a new "group" of trees is initiated through the patchy mortality of the existing overstory. Increased surface fuel loads from this mortality would create a locally intense burn during the next fire, leading to the formation of an amenable microsite for ponderosa pine regeneration with exposed mineral soil, abundant light, low surface fuels with slow fuel accumulation, and little competition from herbaceous vegetation (Rummell 1951, Cooper 1960, Minore 1979, Agee 1993, Stephens et al. 2008). Subsequent partial disturbances and competition are likely to thin this regeneration heterogeneously; reducing the aggregation of trees over time (Pielou 1960, Mast and Veblen 1999, Woodall 2000, Mast and Wolf 2004, Youngblood et al. 2004, Das et al. 2008). Furthermore uneven competition for resources within the group is likely to lead to size differentiation among the regeneration. In a few cases, this process of partial disturbances and self-thinning is likely to result in pairs or single isolated trees. Eventually the senescence and mortality of older trees followed by fire will lead to the creation of new safe-sites, and the process will begin anew with seed source from adjacent trees.

While high levels of aggregation have been reported in ponderosa pine forests of the Southwest U.S., Abella and Denton (2009) reported that there was less aggregation of trees on sites with poor productivity. Competition for limited resources is likely on sites with poor productivity, leading to a greater prevalence of single isolated trees. The lower montane forests of the Front Range are generally less productive than those of the Southwest, suggesting that there should generally be less aggregation, except where the microsites are more mesic. Site to site variation, influenced by variation in site productivity, was probably a notable feature of the Front Range historically.

In addition to ponderosa pine, the lower montane forests of the Front Range also contain Douglas-fir. Differences in the ecological requirements of ponderosa pine and Douglas-fir are likely to result in differences in their fine-scale spatial patterns of trees. Douglas-fir has a wider regeneration niche (Hermann and Lavender 1990), suggesting that the "safe-sites" process is unlikely to be as influential on Douglas-fir spatial patterns; however, Douglas-fir is sensitive to fire and post-fire survivors are likely to be strongly aggregated into areas which did not burn (Steinberg 2002).

3.2 Likely consequences of stand-scale forest structures

The fine-scale spatial patterns of trees are likely to influence a number of ecological processes and human values. Similar to the driving processes creating these patterns, there is little Front Range-specific research; however, broad studies linking pattern and process (sensu Turner 1989) are likely to be applicable to this ecosystem too.

Trees influence their surrounding area through utilizing resources, casting needles and cones, and creating shadows (Figure 2). Therefore, fine-scale tree patterns influence the physical environment and availability of resources to neighboring plants, including light, snow retention, soil chemistry and wind flow (Bruckner et al. 1999, Battaglia et al. 2002, North et al. 2004, Woods et al. 2006, Sprugel et al. 2009, Varhola et al. 2010, Pimont et al. 2011). As a consequence of these neighborhood effects, forest dynamics processes such as recruitment, growth and mortality are influenced by fine-scale tree patterns (Stiell 1978 and 1982, Biondi et al. 1994, Frelich et al. 1998, Van Pelt and Franklin 1999 and 2000, Palik et al. 2003, Boyden et al. 2005, Das et al. 2008, Sánchez Meador et al. 2009). In addition, these patterns may influence understory plant communities, wildlife habitat and behavior, soil microbial communities, and the spread of insects and disease (Turner and Franz 1985, Olsen et al. 1996, Long and Smith 2000, Buchanan et al. 2003, North et al. 2005, Shaw et al. 2005, Dodd et al. 2006, Gundale et al. 2006, Laughlin et al. 2006, Fettig et al. 2007, Dodson et al. 2008).

Figure 2.
A ponderosa pine stand less than one-year post-treatment on the Uncompaghre Plateau. Note the presence of groups of trees with openings between. (Credit: Yvette Dickinson).

Importantly, the spatial patterns of trees may also influence the distribution of fuels and behavior of wildfires (Thaxton and Platt 2006, Beaty and Taylor 2007, Mitchell et al. 2009, Pimont et al. 2011). Specifically, the presence of large understory vegetation under the canopy may act as ladder fuels, encouraging the movement of surface fires into the crown. Furthermore, the casting of needles and cones and the creation of deep shade that hinders understory growth also influences the surface fuels. On the other hand, the presence of openings in the canopy is likely to hinder the spread of crown fires.

Finally, the fine-scale spatial patterns of trees are likely to influence the aesthetic values of a forest stand. Specifically, there is a general preference for varied tree sizes and spacing, including the presence of large character trees (Ribe 1989). Many are opposed to the "jail-bar" or "plantation-like" appearance of stands with homogeneously pole-sized and evenly spaced trees (Figure 3). Anecdotally, stands with open park-like forest structures are thought to be preferred for recreation, while homeowners within the wildland-urban interface may prefer more dense stands to provide audio and visual screening from neighbors.

3.3 Undesirable stand-scale forest structures

The following are recognized as undesirable conditions at the stand-scale:

• Homogenous patterns of approximately similar-sized/shaped trees, whether they are narrowly or widely spaced (e.g., as either large continuous groups, or all single isolated trees).

• Homogeneous patterns of tree groups, where all trees are in groups of approximately the same size/composition/structure with similar spacing among groups (i.e., no inter-group diversity).

• Homogeneous patterns of openings; where all openings are approximately the same size/shape with similar spacing among openings.

• All dense groups of trees are located on difficult terrain or rocky outcrops, but not elsewhere (i.e., letting the feasibility of mechanical treatments dictate the size and location of groups).

• Leaving tall woody understory vegetation that may act as ladder fuels within all groups and result in the loss of many tree groups when fire is reintroduced (through either wildfire or prescribed fire). However, this woody understory vegetation should remain in at least some groups of trees as they may offer important habitat features.

• The removal of all current dead snags or older poor-condition trees that will become dead standing snags or coarse wood in the future.

• The removal of many older/scarred/dead-top character trees; resulting in a stand of predominantly younger straight trees where previously there was more variation in tree-form.

• Contiguous forest canopy throughout the stand, resulting in a stand that lacks any openings.

• Forest structure patterns that do not follow what would be expected given the landform characteristics (i.e., predominantly single isolated trees in a mesic swale, or dense groups of trees on ridgelines and outcrops with shallow low-productivity soils).

Figure 3.

Approximately evenly-spaced even-sized ponderosa pines within a stand (Credit: FR-CFLRP ecological monitoring 2012).

Figure 4.

An area of high density ponderosa pine left within a restored stand on the Pike National Forest. (Credit: FR-CFLRP ecological monitoring 2012).

3.4 Desired stand-scale forest structures

Based on the information summarized above and expert discussions, the following are recognized as desirable conditions at the stand-scale. It should be noted that the specific structure created through restoration should vary among stands, and where a range of desired conditions are presented, all conditions within the range should be present somewhere within the landscape.

• Generally, treatments should create openings (Figures 5 and 6), groups of trees and single isolated trees within stands. The proportion and size of these openings, groups and single-trees should vary within and among stands resulting in the desired conditions identified at the landscape-scale (see 4.4). On low productivity sites (generally drier sites at lower elevations, on south-facing slopes, and/or on ridgelines and convex slopes) there should be a greater prevalence of openings and single-isolated trees. On relatively high productivity sites (generally with higher moisture availability at higher elevations, on north facing slopes, and/or in draws, gullies, and swales) there should be a greater prevalence of larger tree groups with openings and isolated trees.

• Because they are relatively rare, older, scarred and character trees should be protected by leaving them as isolated single trees or, if within tree groups, protected by removing tall understory vegetation that may act as ladder fuels.

• On lower productivity sites (drier sites at lower elevations, on south-facing slopes, and/or on ridgelines and convex slopes) treatments should favor ponderosa pine and preferentially remove Douglas-fir; however, on more productive sites (with higher moisture availability at higher elevations and/or north-facing slopes) a greater diversity of species should be maintained.

• Where present, aspen should be maintained within the stand, and openings around aspen should be created where distinct aspen groves are identified.

• The proportion of trees in groups should vary from stand to stand based on site productivity (as influenced by elevation, topography, landform and soils), ranging from none to nearly all of trees in groups. Generally, there should be fewer trees in groups on sites with lower site productivity. However, the majority of stands across the landscape should have moderate proportions of trees in groups (30 to 60 %). These groups may range in size from 2 to 20 trees with larger groups on more productive sites; however, on most sites the median group size should be small (2–3 trees).

• Groups of trees may be either even or uneven-aged; however, more productive sites (sites with higher moisture availability at higher elevations and/or north-facing slopes) are likely to have greater proportions of uneven-aged groups.

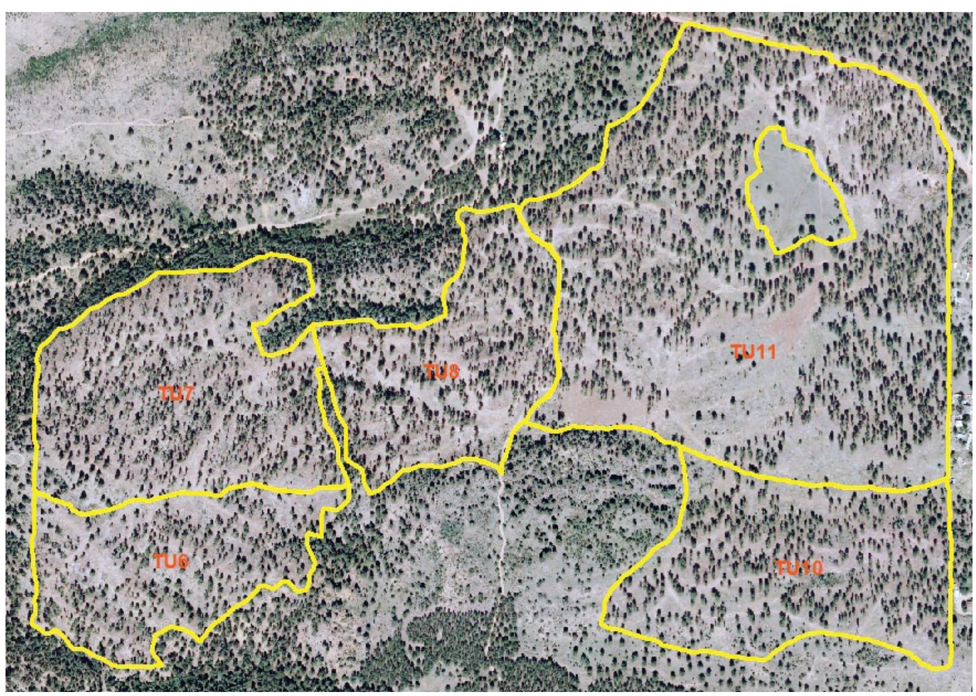
• Both even and uneven-aged stands exist across the landscape; however, there is a predominance of uneven-aged stands with a range of tree sizes, ages and shapes. Uneven-aged stands may consist of groups with a mix of tree ages within each group (intra-group age diversity), or even-aged groups with a variety of ages among the groups (inter-group age diversity).

Figure 5.

A small opening created on a ridge within a dense dry-mixed conifer stand in the Pike National Forest. (Credit: FR-CFLRP ecological monitoring 2012).

Figure 6.

Aerial image of the Ryan Quinlan treatment area (Pike National Forest) after a restoration treatment. Note the presence of large openings within treatment unit 11.
(Credit: Jeff Underhill)



4.0 Landscape-scale forest patterns

Forested landscapes are composed of a mosaic of forest patches (Turner 2001, Chapin et al. 2011), differing in terms of their structures and ecological processes. Adjacent patches interact with each other, influencing cumulative ecosystem function at larger scales (e.g., landscape-scale patterns of fire). However, these interactions are modified by the size, shape, and configuration of the patches. Therefore, we sought to define desired conditions in terms of not only stand-scale forest structures (described above), but also their distribution and proportion across the landscape.

In order to define what is meant by "landscape-scale forest structure," it is necessary first to define the areal extent of the landscape within which patterns will be described. Early in the process of setting landscape-scale desired future conditions, members of the Front Range Roundtable agreed that the landscape for each treatment within the FR-CFLRP would be defined by the surrounding 12 digit-HUC watershed boundaries. These watersheds are approximately 10,000–40,000 acres, and are large enough to place the treatments in their landscape context while being small enough that the treatments may result in detectable changes in landscape-scale forest structure. However, it should be noted that many wildlife guilds and species (e.g., top-predators, ungulates and avian species) are likely to utilize resources at scales much larger than 12 digit-HUC watersheds; therefore, region-wide patterns should also be considered (see 5.0).

4.1 Likely drivers of landscape-scale forest patterns

Past management practices, the influence of the environment on site productivity, and natural disturbance all play a role in the current landscape pattern of forest structure across the Front Range.

Past management practices, including grazing, tree harvesting and fire suppression, have altered the amount and pattern of forests on the Front Range (Marr 1961, Gruell 1985, Veblen and Lorenz 1986 and 1991, Mast et al. 1998, Kaufmann et al. 2000a, Veblen 2000, Kaufmann et al. 2003, Veblen and Donnegan 2005, Sherriff and Veblen 2006, Platt and Schoennagel 2009). Historically these forests were more open and heterogeneous (Kaufmann et al. 2000a, Knight and Reiners 2000), consisting of a mosaic of openings, open woodland and closed canopy across the landscape (Kaufmann et al. 2000b).

Past management has led to the development of contiguous swaths of uncharacteristic dense canopies. Restoration attempts to ameliorate these effects of past management practices, but maintain landscape patterns consistent with what would be expected given the influence of environmental gradients and natural disturbances.

On the Front Range several environmental factors directly influence site productivity and therefore the expected landscape patterns of forest structure (Peet 1981). At the broad regional scale, geo-climatic variations (e.g., the amount and timing of precipitation, or geological parent materials) influence site productivity. The following discussion of environmental gradients at a local scale must be kept within the context of these regional geo-climatic influences (see 5.0).

Within the Front Range, at a local scale, topography, soil characteristics and local-climate all influence site productivity and therefore forest structure. Generally, areas with greater moisture availability are capable of maintaining denser forests and larger trees. Therefore, these forests tend to be denser in draws than on ridges, on north than on south facing aspects, and at high elevation than low elevations. In addition, soil characteristics such as soil depth and texture both influence moisture availability (e.g., the decomposed granitic soils tend to have lower water holding capacity), and therefore forest structure too. Specific patterns in local temperature, precipitation and annual snow accumulation and residence may also influence site productivity.

In addition to environmental influences on site productivity, disturbance regimes also influence forest structure patterns across the landscape (Figures 7 and 8). Mixed fire regimes historically dominated the Front Range (Veblen and Lorenz 1986, Brown et al. 1999, Ehle and Baker 2003), with highly interspersed mixtures of low and high-severity fire effects. Mixed-severity fire regimes tend to occur where small changes in fuels, topography or weather have significant effects on fire behavior and overstory mortality (Halofsky et al. 2011). Regions dominated by mixed fire regimes also tend to have sharp variations in climate, topography and fuels across the landscape, as demonstrated in the Front Range.

During moderate weather conditions, fuels and topography strongly influence fire behavior and therefore the pattern of overstory mortality (Halofsky et al. 2011). Overstory mortality patch size is likely to increase with fire severity. Sites with greater fuel loads (i.e., more productive sites or areas where surface fuels were left untreated) are likely to have greater fire severity than sites with low fuel loads. Therefore, when fire conditions are conducive, more productive sites are likely to experience higher severity fire and larger patch sizes. Patch sizes are therefore likely to be larger on more productive north facing slopes and at high elevations. In addition, patch sizes are likely to be larger on flat areas or mid-slope areas without topographic breaks that modify fire behavior. Generally, the patchiness of forest productivity will lead to patchiness in fuel loads, and therefore patchiness in fire behavior (i.e., patchiness begets patchiness; Halofsky et al. 2011).

That said, the distribution of fuels in addition to the amount of fuels is also influential. Productive sites with mature overstory, low densities of large understory vegetation, and low surface fuel loads, may experience a low severity fire that maintains stand density. In contrast, sites with similar productivity but containing regenerating trees, or high density of tall understory vegetation under a mature canopy may experience a stand replacing fire. The presence of these forest structures is likely to be influenced by the time since a stand replacing disturbance (stand development stage) and climate of the previous years, with high precipitation over a number of years leading to increased growth and regeneration.

However, under extreme weather conditions (hot and dry weather with strong winds resulting in high Haines Index values) the influences of fuels and topography on overstory mortality patterns are superseded. These periods of extreme weather conditions are likely to result in severe fire behavior and large patches of overstory mortality despite the fuel and topographic gradients (Collins and Stephens 2010, Halofsky et al. 2011).

Few studies have specifically quantified the patch-size distribution in the dry forests of the Front Range. Kaufmann et al.'s (2000b) study of a present-day unlogged ponderosa pine landscape in the Cheeseman reservoir area characterized four primary components of the landscape resulting from patterns of fire severity historically: 1) forest patches of varying ages with a distinct tree age-cap; 2) uneven-aged patches without an age-cap that accounted for less than 10 % of the landscape; 3) openings from < 2.5 to > 50 acres, that may have historically constituted up to 10-20% of the landscape and been up to hundreds of hectares in size; and 4) networks of riparian corridors that may be either open or heavily forested. Working in the same landscape, Huckaby et al. (2001) found that ecologically distinct patches delineated from current aerial imagery based on tree density, tree size distribution, and canopy coverage ranged from < 0.25 acres up to 81.5 acres, with

Figure 7.

Flagstaff burn scar west of Boulder, CO (started 26th June 2012) a couple of months after the fire. This fire was started by lightning under high fire hazard conditions; however, the resulting heterogeneous burn scar with live green trees visible within the fire's boundary.
(Credit: Yvette Dickinson)

Figure 8.

Variable survival of trees around the edge of the Hayman fire in 2002. (Credit: Merrill Kaufmann)

a mean size of 8.2 acres. In contrast to Kaufmann et al. (2000b) and Huckaby et al. (2001), studies using spatially sparse historical General Land Office (GLO) data have found that high severity fire may have been widespread periodically (Williams and Baker 2012 a & b).

Generally, fire-dominated forest ecosystems across the western United States demonstrate a consistent negative exponential distribution of forested or non-forested patch sizes (Skinner 1995, Johnson et al. 1998, Piirto and Rogers 2002, Hessburg et al. 2007, Collins and Stephens 2010, Halofsky et al. 2011, Perry et al. 2011), with many small patches (< 9.9 acres each) that collectively occupy a small proportion of the total area (< 50 %), and few large patches (100–1000+ acres) that collectively occupy a large proportion of the total area (> 50 %). However, it is important to note that the factors used to delineate the patch types influence the interpretation of patterns in the landscape-scale forest structure. A variety of patch definitions have been used in the published studies discussed above; furthermore, the specific factors used to delineate patches used in those studies and their average patch sizes are unlikely to be meaningful in the context of this document (see 2.0 for the definitions used in this document). However, in spite of this variation among the studies, the negative exponential patch size distribution holds true across all of these studies in forests dominated by both high and mixed-severity fire regimes.

4.2 Likely consequences of landscape-scale forest patterns

The likely consequences of future changes to landscape patterns of forest structure across the Front Range also need to be considered. There is much uncertainty regarding these likely consequences; however, some general statements can be made.

• **Understory plant species diversity and cover.** Increased landscape heterogeneity of forest structures across the landscape are likely to lead to a greater variety of understory environments and increased diversity of understory plant communities (beta diversity). Furthermore, the understory plant cover is likely to increase in areas with reduced canopy cover.

• **Insect and disease activity.** Increased landscape heterogeneity of forest structures across the landscape is likely to decrease probability of insect or disease outbreaks as only a portion of the landscape is likely to be susceptible at a time (Fettig et al. 2007).

• **Fire.** Increased landscape heterogeneity of forest structure across the landscape is likely to decrease the probability of uncharacteristic severe wildfires across large areas by decreasing the continuity and connectivity of fuels. In addition, increased landscape heterogeneity of fuels is likely to increase heterogeneity of overstory mortality from fire across the landscape.

• **Wildlife habitat.** While landscape-scale patterns of forest structure are known to influence wildlife habitat (Long and Smith 2000, Dodd et al. 2006), generally, the response of wildlife to specific changes in landscape patterns of forest structure is poorly understood. There will also be a range of species-specific responses depending on the characteristics of each species and the wider regional context. Further, many top-level predators are thought to utilize resources at scales much larger than the 10,000–100,000 acre landscape scale as defined in this document. While some species may benefit from changes to landscape patterns of forest structure, others may be negatively affected. Increasing the diversity of forest structures on the landscape may increase diversity of resources available for some wildlife species.

• **Forest dynamics.** Dispersal of seed into disturbed patches is likely to be more effective with more heterogeneous disturbances and smaller patch sizes. The required dispersal distances from surviving trees will be shorter. Therefore, these forests are likely to be more resilient to these disturbances and recover more quickly.

• **Aesthetic values.** Forest treatments across the landscape will alter the aesthetic qualities of the landscape; however, the effect of specific changes on aesthetic values is largely unknown. While it has been generally shown that the public prefers complex forest structures with large trees (Ribe 1989), the post-treatment landscape may be dramatically different from what the current generation has grown used to. The effect may also change over time, as the forests respond to treatments, stumps and coarse wood decay and understory vegetation increases.

• **Recreation values.** Similar to the aesthetic values, increasing heterogeneity and the abundance of open-woodlands is likely to influence recreation values. While the specific changes are unknown, anecdotally it has been observed that reducing tree density and opening up the understory of the forest may increase recreational use of individual forest stands. Increasing the openness of stands across the landscape may increase "dispersed recreation" (outside of designated camping or concessionaire-operated facilities) across the landscape. It is likely that the effect of forest treatments on recreation values is dependent on the specific type of recreation. In addition, the effect may change over time, as the forests respond to treatments.

• **Watershed values.** Changes to forest structure through thinning are known to influence hydrological processes such as snow accumulation, sublimation, interception and evapo-transpiration. For example, evenly-thinned lodgepole pine (*Pinus contorta*) stands in Montana were found to have reduced interception and higher soil water than an unthinned control. In addition, higher snow accumulation was recorded in evenly-thinned stands than in either an unthinned control or a heterogeneous thinned stand with openings (Woods et al. 2006). However, it is hypothesized that the changes following thinning will be less severe than those experienced following a large severe wildfire, particularly in terms of increased hill slope erosion and stream turbidity.

4.3 Undesirable landscape-scale forest patterns

The following are landscape-scale forest structure patterns that are undesirable on the Front Range:

• Continuous homogeneous condition across the landscape, no matter what that condition is. This may include large extents of a) homogeneous closed canopy (Figure 9), b) open non-forested areas (e.g., areas burned by high severity wildfire), or c) repetitive fine-scaled patterns that are homogeneous at large scales.

• Regular pattern of forest patches and openings, consistent in terms of patch size, shape and configuration. An extreme example of this is a checkerboard pattern of forest patches.

• Patterns of forest structure which do not relate to natural topographic gradients (e.g., reduced tree densities on relatively flat draws and ridges with no treatments on steep slopes between may create obvious horizontal bands of dense forest with open canopy above and below) or follow arbitrary straight lines such as management or property boundaries.

• Novel forest structure types that have no historical or current analog that cannot be justified based on sound analysis. It is assumed that forest structures that are consistent with the historical range of variability are more resistant and resilient to disturbance, as forest species have evolved to with the types of disturbances associated with historical forest structures. It is also assumed that wildlife and understory species are adapted to forest conditions consistent with the historical range

Figure 9.

A dense canopy of ponderosa pine blanketing the landscape approximately 15 miles west of Longmont, CO.
(Credit: Google earth)

of variability. However, there is a great deal of uncertainty surrounding the historical range of variability for landscape-scale patterns of forest structure. Under a changing climate, novel forest structures may be required to enhance forest resistance and resilience to novel disturbance regimes. Any management that promotes the establishment of novel forest structures under historically unprecedented climatic conditions must be fully justified by thorough analysis.

• Forest landscapes that are extremely fragmented by development so as to be essentially urban or suburban throughout. While this is outside the scope of the Front Range Roundtable's work, the absence of large contiguous natural areas would be an undesirable condition.

4.4 Desired landscape-scale forest patterns

Desired conditions of forest structure at the landscape scale are context specific. The local context needs to be considered when setting specific desired conditions, such as the protection of homes from wildfire within wildland-urban interface, protection of riparian areas, and feasibility of treatments requiring large machinery.

In the literature there are debates about the exact proportion of the landscape that was open as a result of high overstory mortality fires (Brown et al 1999, Veblen et al. 2000, Huckaby et al. 2001, Kaufmann et al 2000a & b, Kaufmann et al 2003, Ehle and Baker 2003, Veblen and Donnegan 2005, Sherriff and Veblen 2006, Schoennagel et al. 2011, Williams and Baker 2012 & 2014, Fulé et al. 2014, Odion et al. 2014). Despite this debate, it is agreed that at least some of the Front Range experienced fires that resulted in high overstory mortality and open patches.

Some generally desirable trends in forest structure across the landscape have been identified:

• Higher tree densities within patches on north aspects than on south aspects; at higher elevations with mixed conifer than lower elevations with ponderosa pine forest types, and in draws than on ridges.

• Larger patches (forested or open) should occur on north facing slopes compared to south facing slope (perhaps a single patch comprising the whole slope on north facing aspects). Larger patches (forested or open) at higher elevations with mixed conifer forest types (in the order of tens to hundreds of acres) than lower elevation with ponderosa forest types.

• Steep topography tends to facilitate fire movement into the canopy; therefore, we expect that larger patches (forested or open) should occur on steep topography. However, where the topography is highly dissected, substantial topographic breaks should restrict patch size.

• Openings relatively less common at higher elevations and on north-facing aspects than at lower elevations and on south-facing aspects. Where openings occur at higher elevations, they tend to be larger and continue across topographic breaks mimicking the effects of more severe fire behavior under more extreme weather conditions.

• Generally a negative exponential pattern of patch sizes within 12 digit-HUC watersheds with many small patches (< 10 acres) that occupy < 50 % of total area; and few large patches (> 25 acres) which occupy > 50 % of total area.

• Patches (forested or open) should generally follow topographic and environmental gradients; and not arbitrary management boundaries (e.g., property boundaries, or operability slope cut-offs for machinery).

• It is expected that aspen will benefit from decreases in coniferous canopy cover across the landscape. Furthermore, where aspen is present it should be protected.

5.0 The regional scale

The landscape-scale patterns described above occur at the 12 digit-HUC watershed scale; however, patterns in forest cover may occur at even larger regional scales (Figure 10). Furthermore, top predators are likely to utilize resources at scales much larger than 12 digit-HUC watersheds, and may be sensitive to changes at this much larger scale.

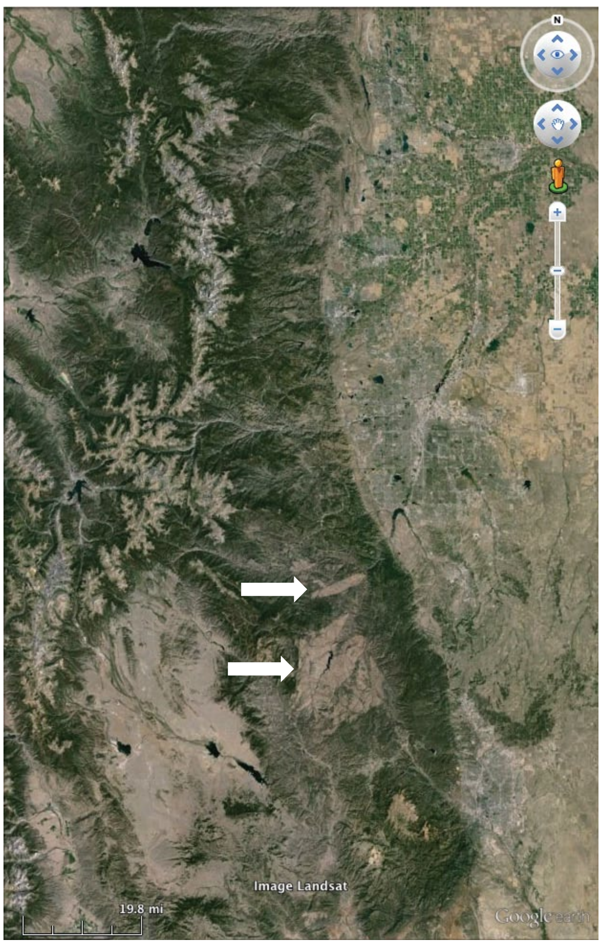


Figure 10.

Satellite imagery of the Colorado Front Range region taken on 4 September 2013. The burn scars of the Buffalo creek and Hayman fires are clearly visible at the southern end of the Front Range. (Credit: Google earth).

Figure 11.

The extent of granitic soils on the Front Range (USGS 2005). The black line indicates the extent of the FR-CFLRP.

Variations among landscapes across Colorado's Front Range are primarily driven by biophysical and climatic gradients; however land-use patterns may also differ at this scale. While these gradients are largely beyond the control of forest managers, they should be considered when developing specific desired conditions at the landscape scale. For example, restoration treatments implemented at similar altitudes in the northern and southern Front Range are likely to differ due to differences in geology (Figure 11), temperature (Figure 12), precipitation (Figure 13) and seasonal variation. For example, soils derived from decomposed granite dominate the southern Front Range. These soils have low water carrying capacity and poor fertility. Therefore, the desired conditions described at the stand- and landscape-scales for drier sites with poor fertility soils will dominate this part of the region.

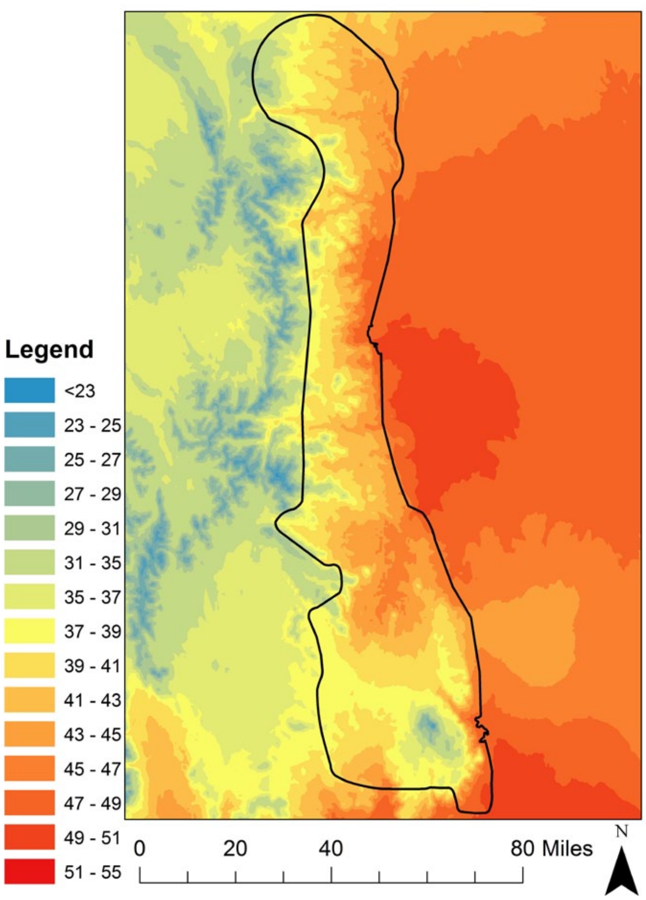


Figure 12.

Mean annual temperature 1971-2000 (°F) of the Front Range derived from PRISM (NRCS 2012a). The black line indicates the extent of the FR-CFLRP.

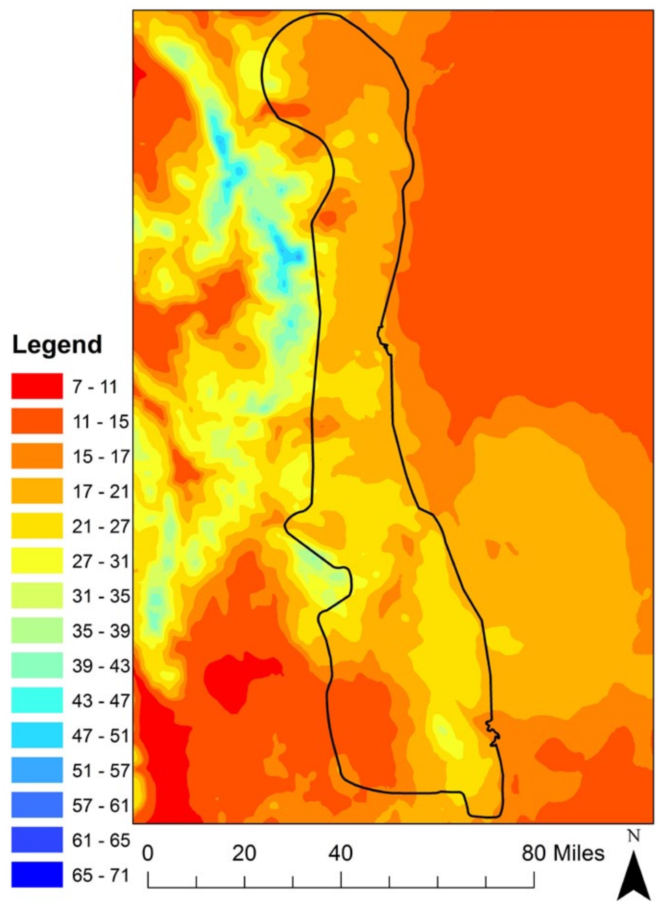


Figure 13.

Mean annual precipitation 1971-2000 (inches) of the Front Range derived from PRISM (NRCS 2012b). The black line indicates the extent of the FR-CFLRP.

6.0 Using desired conditions to monitor restoration effectiveness

The desired conditions described in this document were developed to aid in the design and monitoring of forest restoration treatments on the Front Range. The FR-CFLRP is currently using Common Stand Exam (CSE) protocols to measure traditional forestry measures such as tree density, basal area, regeneration and fuel loads to monitor treatment effectiveness (Clement and Brown 2011). This protocol includes the establishment of permanent sampling plots, using a variable sized prism-plot for the overstory, fixed sized plots for regeneration and Brown's transects to estimate surface fuel loads.

Furthermore, the FR-CFLRP undertakes annual field trips to qualitatively evaluate treatments at selected sites. While these field trips do not result in quantitative metrics of forest structure, they may be useful in monitoring forest structure at both the stand and landscape-scales.

In addition, methods to quantify within-stand spatial heterogeneity of the forest structure using publicly available aerial imagery have been developed by Pelz and Dickinson (2014). These methods utilize multispectral analysis and NAIP (National Aerial Imagery Program) imagery with a 7.9 ft (2.4 m) resolution to map the canopy cover within the treatment units. The spatial distribution of the canopy cover is then quantified using a patchwork mosaic approach.

Similar methods are currently being developed for characterizing landscape scale forest structure using remote sensing methods. It is proposed that aerial imagery and/or LANDSAT data may be used to map canopy density at a 98.4 ft (30 m) resolution throughout an entire landscape. These maps may then be categorized into dense (71–100 %), moderate (41–70 %), low (11–40 %), sparse canopy cover (1–10 %) and openings (0 %). The spatial distribution of these categories quantified using an approach similar to the within-stand scale analyses.

The following tables describe possible metrics that may be used to monitor treatment effectiveness in achieving the desired conditions described above at the within-stand scale (Table 1) and at the landscape scale (Table 2), and the expected trends under successful restoration.

7.0 Research needs

The desired conditions presented here are based on the best available science and expert opinion, but should be viewed as preliminary. They should be regularly reviewed and updated as the science advances.

In the course of deriving these desired conditions, several research needs were identified:

• The current reconstructions of the historic range of variation if Front Range forests need further refinement to reflect the full range of forest structures that would have been present across various biophysical settings through time.

• Our current understanding of the ecological consequences of using variable density ("groupy-clumping") thinning to restore forest stands is poor. Furthermore, there is a need to understand the influence of these restoration treatments on landscape-scale ecological processes. Therefore, further research is needed to understand the influence of these types of treatments on processes such as wildlife habitat values, understory vegetation, soil development, hydrologic processes and fire behavior.

• Further work is needed to clarify the social acceptance of these stand- and landscape-scale desired conditions within the wider Front Range community. Attempts to restore Front Range landscapes are likely to fail if there is little social support for the restoration efforts.

8.0 Acknowledgments

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Table 1.

Metrics to monitor within-stand forest structure using field data collected using the Common Stand Exam protocol and analysis of aerial imagery. These metrics may be analyzed at the stand- or project- (typically consisting of multiple neighboring stands being treated in conjunction) scales.

Metric	Definition, interpretation and units	Expected trends with successful restoration
Common Stand Exam		
Standard error of basal area among CSE plots	The variation of basal area (ft^2/acre) measurements among the CSE plots will provide a non-spatial indicator of variation across the treatment unit.	Maintain or increase
Standard error of tree density among CSE plots	The variation of tree density (trees/acre) measurements among the CSE plots will provide a non-spatial indicator of variation across the treatment unit.	Maintain or increase
Aerial Image Analysis (Mapping the presence of canopy cover within stand using 4-band 2.4m resolution imagery)		
Percentage of landscape [treatment unit] (PLAND) occupied by coniferous canopy cover.	Total area covered by canopy as a percent of total treatment unit area (%).	Decrease
Largest patch index (LPI) for coniferous canopy.	The percentage of total landscape area comprised by the largest tract of contiguous canopy (%).	Decrease
Edge density (ED) of coniferous canopy cover.	The length of canopy edge per unit area (m/ha). Adjacent canopy influences openings and *vice versa,* therefore edge effects are an important driver of ecological processes. Edge density is an indicator of the prevalence of edge effects.	Increase
Patch area (PA) of coniferous canopy cover. Mean, range, standard deviation reported. Frequency distribution graphs may also be plotted.	The size of contiguous tracts of canopy (ha).	Decrease in mean with increase in range and standard deviation
Perimeter area ratio (PARA) for canopy. Mean, range, and standard deviation reported. Frequency distribution graphs may also be plotted.	The ratio of the perimeter of a contiguous tract of canopy to its area is a measure of its shape (unitless). Large perimeter-to-area ratios indicate convoluted or complex edges with greater proportions of the area influenced by neighboring patches.	The perimeter-to-area ratio will increase as the stand becomes more fragmented and/or the canopy becomes more irregular with complex and convoluted edges.
Patch density (PD) of coniferous canopy.	Simple measure of the density of contiguous canopy tracts per 100 hectares. This is strongly influenced by the size of contiguous canopy tracts.	Increase
Euclidean distance (ED) to nearest similar patch of coniferous canopy. Mean, range and standard deviation reported. Frequency distribution graphs may also be plotted.	The shortest straight-line distance between the focal contiguous tract of canopy (m) and its nearest neighbor is a simple measure of patch context used to quantify canopy isolation.	Increase in mean distance, with increase in range and standard deviation.
Euclidean distance between a randomly generated point and the nearest contiguous tract of canopy. Mean, range and standard deviation reported. Frequency distribution graphs may also be plotted.	The shortest straight-line distance between a random point (generated at the same density as the canopy patches) and the nearest contiguous tract of canopy (m) is a simple indicator of the prevalence and size of canopy gaps.	Increase in mean distance, with increase in range and standard deviation.

Table 2.

Metrics to monitor forest structure at landscape-scale using remote sensing methods (Mapping of dense, moderate, low and sparse canopy cover and openings at 30m resolution).

Metric	Definition, interpretation and units	Expected trends with successful restoration
Percentage of landscape [12 digit-HUC] (PLAND) occupied by dense, moderate, low and sparse coniferous canopy cover, and openings.	Total area covered by canopy as a percent of total treatment unit area (%).	Decrease in dense and moderate canopy cover; and increase in low and sparse canopy cover and openings.
Largest patch index (LPI) of dense, moderate, low and sparse coniferous canopy cover, and openings.	The percentage of total landscape area comprised by the largest patch (%). It is a measure of the dominance of the largest patch of each patch type.	Decrease in dense and moderate canopy cover; and increase in sparse and low canopy cover and openings.
Edge density (ED) for entire landscape.	The length of patch edge per unit area (m/ha). Edge effects where adjacent patches influence each other are an important driver of ecological processes in complex landscapes. Edge density is therefore the likely influence of edge effects in the landscape.	Increase
Patch area (PA) of dense, moderate, low and sparse coniferous canopy cover, and openings. Mean, range, standard deviation reported. Frequency distribution graphs of patch area may also be plotted.	The size of a patch by type (ha).	Decrease in mean for dense and moderate canopy cover, and increase in low and sparse canopy cover and openings. Increase in range and standard deviation for all patch types.
Perimeter area ratio (PARA) for entire landscape. Mean, range, and standard deviation reported. Frequency distribution graphs may also be plotted.	A ratio of the perimeter of a patch to its area is a measure of the shape of a patch (unitless). Edge effects where adjacent patches influence each other are an important driver of ecological processes in complex landscapes. Large perimeter-to-area ratios indicate convoluted or complex edges with greater proportions of the area influenced by neighboring patches.	As the stand becomes more fragmented and/or patches become more irregular with complex and convoluted edges the perimeter-to-area ratio will increase.
Patch density (PD) of entire landscape.	Simple measure of the density of patches per 100 hectares. Patch density is an indication of the prevalence of patch types (i.e., dense, moderate, low and sparse coniferous canopy cover, and openings) and is strongly influenced by the size of patches.	Increase as large patches are broken down into smaller patches.
Euclidean distance (ED) to nearest similar patch of dense, moderate, low and sparse coniferous canopy cover, and openings. Mean, range and standard deviation reported. Frequency distribution graphs may also be plotted.	The shortest straight-line distance between the focal patch (m) and its nearest neighbor of the same type is a simple measure of patch context used to quantify patch isolation.	Increase in mean for dense and moderate canopy and decrease for sparse and low canopy and openings, with increase in range and standard deviation for all patch types.

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About the Colorado Forest Restoration Institute

The Colorado Forest Restoration Institute (CFRI) was established in 2005 as an application-oriented program of the Department of Forest & Rangeland Stewardship in the Warner College of Natural Resources at Colorado State University. CFRI's purpose is to develop, synthesize, and apply locally-relevant science-based knowledge to achieve forest restoration and wildfire hazard reduction goals in Colorado and the Interior West. We do this through collaborative partnerships involving researchers, forest land managers, interested and affected stakeholders, and communities. Authorized by Congress through the Southwest Forest Health and Wildfire Prevention Act of 2004, CFRI is one of three Institutes comprising the Southwest Ecological Restoration Institutes, along with centers at Northern Arizona University and New Mexico Highlands University.

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