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Principles and Practices for the Restoration of Ponderosa Pine and Dry Mixed-Conifer Forests of the Colorado Front Range

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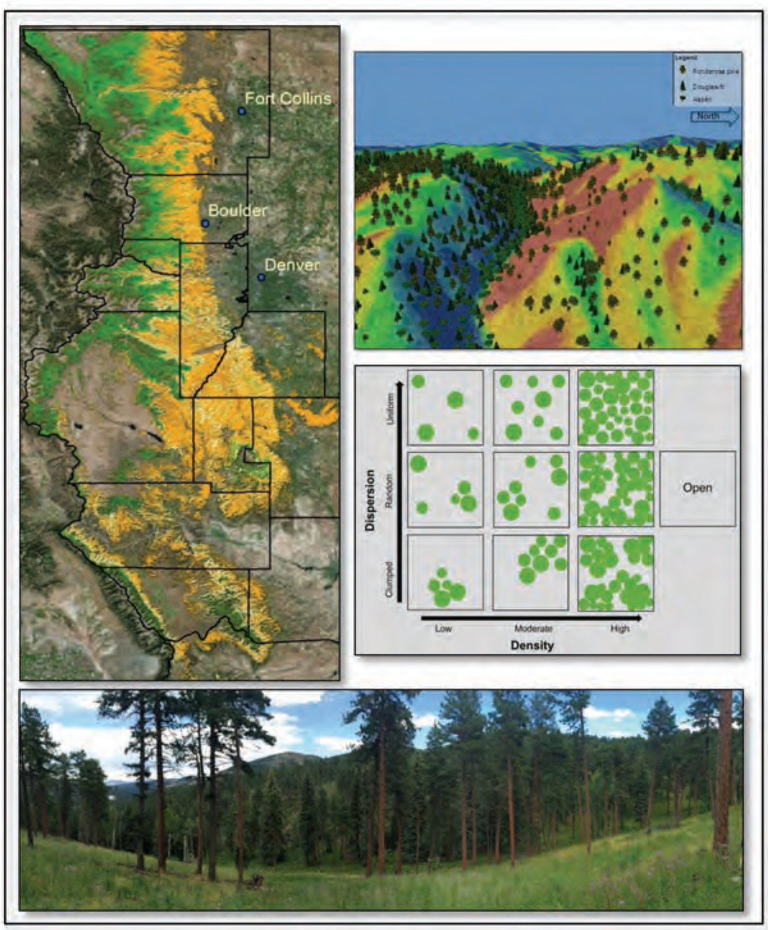

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Abstract

Wildfires have become larger and more severe over the past several decades on Colorado's Front Range, catalyzing greater investments in forest management intended to mitigate wildfire risks. The complex ecological, social, and political context of the Front Range, however, makes forest management challenging, especially where multiple management goals including forest restoration exist. In this report, we present a science-based framework for managers to develop place-based approaches to forest restoration of Front Range ponderosa pine and dry mixed-conifer forests. We first present ecological information describing how Front Range forest structure and composition are shaped at multiple scales by interactions among topography, natural disturbances such as fire, and forest developmental processes. This information serves as a foundation for identifying priority areas for treatment and designing restoration projects across scales. Treatment guidelines generally reduce forest densities and surface and crown fuels, enhance spatial heterogeneity across scales, and retain drought- and fire-tolerant species, old trees, and structures important for wildlife. Implementation of these guidelines is expected to enhance forest resilience to disturbance and climate change, as well as sustain important ecosystem services. Finally, this report emphasizes the importance of adaptive management and learning through monitoring and experimentation to address uncertainties inherent in the restoration process.

Keywords: disturbance regime, forest structure, resilience, restoration, scale, spatial heterogeneity, topography

Front cover: clockwise from top left: Map of distribution of forest types across the Colorado Front Range; diagram showing how forest structure can vary based on topography and moisture; diagram depicting hypothetical combinations of tree density and dispersion; posttreatment stand condition at the West Ranch treatment area in Jefferson County, near the town of Conifer, Colorado (photo: J. Hansen, Jefferson Conservation District, used with permission).

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COLORADO FOREST RESTORATION INSTITUTE

Colorado State University

Contents

1. Introduction

1.1 Definitions and Regional Context for Forest Restoration

Ecological restoration is defined by the Society for Ecological Restoration (SER) as "the process of assisting the recovery of an ecosystem that has been damaged, degraded, or destroyed" (SER 2004: p. 3). Ecological restoration has been a guiding concept for natural resource management for the last several decades, and was developed to address concerns over loss of ecological function in ecological systems that have departed from their natural or historical range of variability (HRV). The term "restoration" implies a return to some former ecological state or condition, and indeed the concept of HRV is used frequently in restoration to guide the development of desired conditions to be achieved through restoration activities on the ground. Increasingly, however, restoration is going beyond management focused solely on restoring ecosystem characteristics consistent with the HRV, and rather using the HRV to understand the ecological drivers underpinning ecological resilience, or the capacity of an ecosystem to recover from disturbance without loss of inherent ecosystem functional characteristics (Holling 1973; Lake 2013; Walker et al. 2004). (Please see glossary for definitions of these and other terms used in this report.) Likewise, natural resource management agencies are increasingly invoking the concept of resilience in management planning frameworks, especially in light of climate change and predicted increases in disturbances such as wildfire and insect outbreaks (Benson and Garmestani 2011).

In the western United States, much emphasis has been placed in the last several decades on the proactive restoration of dry coniferous forest types, including ponderosa pine (*Pinus ponderosa*) and dry mixed-conifer forests (Allen et al. 2002; Covington and Moore 1994; Hessburg et al. 2015; Moore et al. 1999). These forest types are widely distributed throughout the western United States, typically occurring on relatively moisture-limited sites at lower elevations in the Rocky Mountains, the Black Hills, the Cascade Range, and the Sierra Nevada (Daubenmire 1943; Oliver and Ryker 1990; Peet 2000). Prior to Euro-American settlement, these forest types are believed to have experienced more frequent low- and mixed-severity fires compared to the modern fire suppression era, and these relatively frequent fire events undoubtedly were important in maintaining diverse forest structures and compositions across the landscape (Fulé et al. 2009; Kaufmann et al. 2005; Perry et al. 2011; Peterson et al. 2005).

Concern over increases in wildfire activity, community safety within the wildland-urban interface, and loss of forest function and resilience in the face of climate change has prompted fuels reduction and forest restoration work throughout the western United States (Litschert et al. 2012; North et al. 2009; Reynolds et al. 2013; Schwilk et al. 2009; Stephens et al. 2012b; Westerling et al. 2006). This work has been promoted largely by Federal programs such as the National Fire Plan (USDOI and USDA 2000), the Healthy Forests Restoration Act of 2003, the Collaborative Forest Landscape Restoration Program, the Natural Resources Conservation Service's Environmental Quality Incentives Program, and more recently the National Cohesive Wildland Fire Management Strategy (USDOI and USDA 2014). In Colorado, State programs such as the Department of Natural Resources Wildfire Risk Reduction Grant Program and the State Forest Service's Community Forest Restoration Grant Program have also been instrumental in promoting proactive forest management. The emphasis in this type of proactive restoration management is on creating forest conditions that will be resilient to future disturbances such as wildfire and insect epidemics, and will also moderate the severity of those disturbances if they occur (Hessburg et al. 2015; Reynolds et al. 2013). Thus, this type of restoration differs from postdisturbance, reactive stabilization and restoration efforts such as those that are often implemented in sites recently affected by high-severity fires, flooding, erosion, insect outbreaks, or similar events.

1.2 Forest Restoration on the Colorado Front Range

The evolution toward proactive forest restoration on the Colorado Front Range has occurred over the past 20+ years, catalyzed in large part by the numerous, large high-severity wildfires that have occurred (table 1). The Black Tiger Fire in Boulder County in 1989 is often cited as Colorado's first large wildland-urban interface fire and was notable for its extreme fire behavior and the high number of homes it destroyed (National Fire Protection Association 1989). The 11,900-acre Buffalo Creek Fire in 1996 resulted in considerable runoff and erosion that adversely affected downstream reservoirs critical to the City of Denver's water supply (Culver et al. 2001). The Black Tiger and Buffalo Creek Fires raised awareness about current forest and fuel conditions on the Front Range and the potential for negative outcomes associated with extreme fires, especially in the wildland-urban interface where homes and important community infrastructure are at risk. Numerous wildfires since the Buffalo Creek Fire have continued to highlight the issue of high fuel loads and high wildfire risk in many areas of the Front Range, with wildfire activity and area burned expected to increase in the future

Table 1—Significant wildfires that have occurred since the 1980s on the Colorado Front Range. Adapted from Graham et al. (2012); updated to include fires occurring after 2011.

Fire	Year	Acres
Black Tiger	1989	1,778
Olde Stage	1990	3,000
Buffalo Creek	1996	11,900
Hi Meadow	2000	10,800
Bobcat Gulch	2000	10,599
Snaking	2002	2,590
Schoonover	2002	3,860
Hayman	2002	137,760
Big Elk	2002	4,413
Overland	2003	3,439
Picnic Rock	2004	8,908
Olde Stage	2009	3,169
Fourmile Canyon	2010	6,181
Crystal	2011	2,940
Lower North Fork	2012	4,140
Hewlett Gulch	2012	7,685
High Park	2012	87,284
Waldo Canyon	2012	18,247
Black Forest	2013	14,280

with climate change (Litschert et al. 2012; Liu et al. 2015; Westerling et al. 2006). Notable examples of Front Range wildfires include the Hayman Fire in 2002, the Fourmile Canyon Fire in 2010, the Lower North Fork, High Park, and Waldo Canyon Fires in 2012, and the Black Forest Fire in 2013 (table 1). The Hayman Fire remains the largest fire recorded on the Front Range at 137,760 acres.

Front Range wildfires have had high ecological and economic costs and have raised concern over the long-term sustainability of Front Range forests. In many cases, watershed impacts have been severe and have compromised important ecological functions and ecosystem services such as water delivery (Lynch 2004; MacDonald and Stednick 2003). For example, Denver Water has spent an estimated $28 million in repairs to water collection infrastructure in the wake of the Buffalo Creek and Hayman Fires combined (Denver Water 2017; LeMaster et al. 2007). Water quality impacts (elevated nitrates and turbidity), as well as increased temperature, were documented in stream water as a result of the Hayman Fire; impacts persisted for at least 5 years after the fire and were especially acute during spring runoff (Rhoades et al. 2011). Critical habitat for some species of wildlife can be lost as well. For example, an estimated 50 percent of the entire habitat range of the Federally-threatened Pawnee montane skipper (*Hesperia leonardus montana*), an endemic butterfly of the southern Front Range, has been affected by the Hayman, Schoonover, Buffalo Creek, and Hi Meadow Fires (Kotliar et al. 2003; Sovell 2013). This species requires open ponderosa pine woodlands where frequent fire maintains both its nectar plant, prairie gayfeather (*Liatris punctata*), and its host plant, blue grama (*Bouteloua gracilis*), for egg laying and larvae feeding (U.S. Fish and Wildlife Service 2011). Aquatic species such as the greenback cutthroat trout (*Oncorhynchus clarki stomias*) are also vulnerable due to postfire runoff and sedimentation and subsequent changes in water quality, temperature, and oxygen levels (Kershner et al. 2003).

Lack of natural tree regeneration in postfire environments is a concern as well (Turner et al. 2013), with recent studies showing limited regeneration of conifers, especially ponderosa pine, within large, stand-replacing burn (fire or patch within a fire where all or nearly all trees are killed) patches due to the lack of seed trees (Chambers et al. 2016; Rother and Veblen 2016) (fig. 1; see section 3.5 for definitions and descriptions of fire severity). Even in the presence of seed trees, Rother et al. (2015) suggest that regeneration is limited due to dry, unfavorable conditions for seedling survival and

Figure 1—Treeless landscape within the 2002 Hayman burn 13 years after the fire. Cheesman Reservoir can be seen in the distance (photo: P. Brown, Rocky Mountain Tree-Ring Research, used with permission).

growth. These large, stand-replacing burn patches are thus subject to ecological state-transitions from forest to grasslands or shrublands (Romme et al. 1998; Savage et al. 2013; Stephens et al. 2013). Community protection and safety, invasive species, loss of recreational opportunities, and negative impacts to local economies are additional concerns associated with large, high-severity wildfire on the Front Range (Fornwalt et al. 2010; Western Forestry Leadership Coalition 2010).

The increase in wildfire activity on the Front Range in the last few decades has spurred investments in forest management to reduce wildfire risks and has catalyzed the formation of numerous collaborative groups representing the various agencies and organizations involved in natural resource management on the Front Range. Such groups have formed to increase the pace and scale of treatment efforts by combining and leveraging resources, including planning and implementation capacity, as well as funding. The Upper South Platte Watershed Restoration Project is an early example of such collaboration, formed in 1998 after the Buffalo Creek Fire to assess watershed conditions and prioritize forest management efforts within the Upper South Platte watershed (Culver et al. 2001). The Front Range Fuels Treatment Partnership (FRFTP) followed in 2003, after the 2002 Hayman Fire, to address wildfire risks and develop treatment strategies across the Front Range. The FRFTP evolved into the Front Range Fuels Treatment Partnership Roundtable (FRFTPR; now the Front Range Roundtable) as a more formal coalition of State and Federal government agencies, local governments, environmental organizations, the scientific community, and the public, with the goal of creating a more resilient Front Range forested landscape through collaboration, sound land management, and community engagement (FRFTPR 2006). The Front Range Roundtable continues to be the overall organizing entity for forest restoration on the Front Range, but smaller-scale, geographically focused initiatives such as the Upper Monument Creek Landscape Restoration Initiative have also recently formed to take a targeted approach to forest restoration in specific landscapes (Upper Monument Creek Collaborative [UMCC] 2014).

A common vision among these various stakeholder groups is to promote the proactive restoration of forest structure and ecological processes in ponderosa pine and dry mixed-conifer forests of the Front Range. Front Range forests developed with disturbances such as fire that shaped the landscape dynamically over space and time, and created heterogeneous vegetation patterns that conferred resilience to subsequent disturbances and changes in climate. Ecological restoration in the Front Range aims not only to increase the adaptive capacity and resilience of these forests to future wildfires, bark beetle (*Dendroctonus* spp.) outbreaks, and climate change, as well as to mitigate wildfire hazards, but also to protect values at risk in the rapidly expanding wildland-urban interface.

The Front Range Roundtable identified about 1.5 million acres in need of forest management to mitigate wildfire hazard, protect communities, and restore forest structure and composition across the Front Range (FRFTPR 2006). This land area stretches from El Paso County in the south to Larimer County in the north, and primarily includes ponderosa pine and dry mixed-conifer forests occurring from about 5,500 to 9,300 feet in elevation (fig. 2). Enhancing forest structural and age-class diversity and reestablishing a complex landscape mosaic to enable more low- to mixed-severity fires and reduce the likelihood of broad-scale forest loss are primary restoration

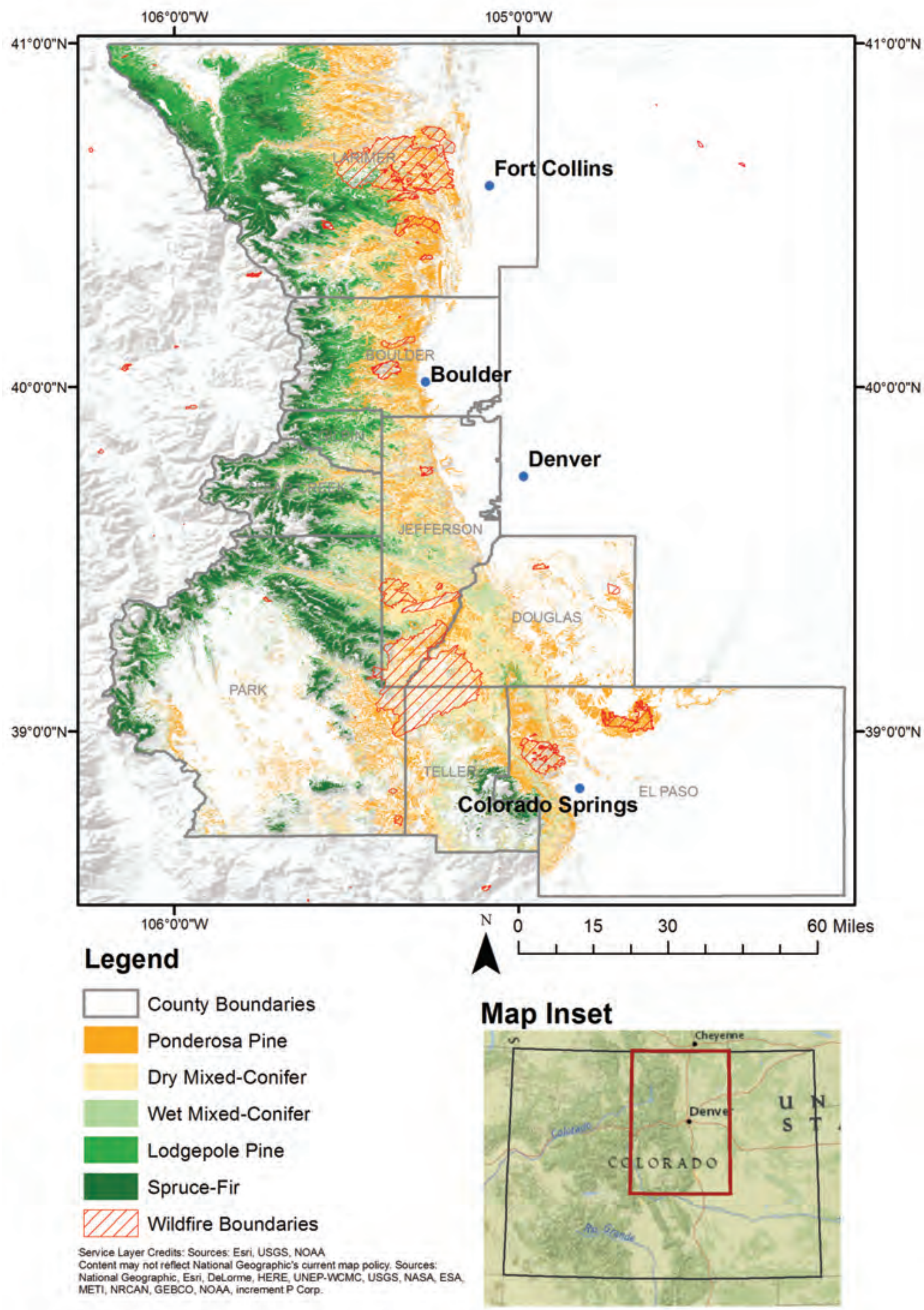

Figure 2—Primary forest types of the Colorado Front Range based on land cover maps of the Southwest Regional Gap Analysis Project (Prior-Magee et al. 2007). Areas mapped as Rocky Mountain Ponderosa Pine Woodland (S036) and Rocky Mountain Montane Dry-Mesic Mixed Conifer Forest and Woodland (S032) ecological systems are the emphasis of this report.

goals defined by the Roundtable (Clement and Brown 2011; Dickinson and Spatial Heterogeneity Subgroup of the Front Range Roundtable [SHSFRR] 2014; FRFTPR 2006). Recognition that fire and other disturbances have always played a role in shaping Front Range forests and working with natural ecological processes to enhance landscape resilience have become cornerstones of the restoration process as well.

1.3 The Need for This Document

Front Range scientists and managers generally agree on the need for restoration of ponderosa pine and dry mixed-conifer forests, especially in lower montane settings of the Front Range (Baker et al. 2007; Brown et al. 2015; Colorado State Forest Service 2009; Dennis and Sturtevant 2007; Dickinson 2014; Dickinson and SHSFRR 2014; FRFTPR 2006; Kaufmann et al. 2006; Sherriff et al. 2014; UMCC 2014; Veblen and Donnegan 2005). However, uncertainties remain about where restoration should occur and if it is compatible with other forest management practices such as fuels reduction. Forest management on the Front Range occurs within extremely complex social, economic, political, and ecological contexts, with factors such as climate change presenting additional challenges. Forest managers responsible for navigating these complexities could benefit from an overall framework that provides guidance and a process for landscape-to stand-scale treatment planning and implementation on the Front Range. This document was developed to address: (1) integration of multiple management goals, (2) information specific to the Front Range, (3) restoration within a mixed-severity fire regime, (4) desired conditions, (5) planning and prioritizing treatments, (6) treatment design and implementation, and (7) climate change.

Integration of multiple management goals—Multiple management goals often exist on the Front Range, such as protecting values at risk, enhancing forest resilience, and sustaining biodiversity and wildlife populations. Management activities to support these goals include fuels reduction, forest restoration, and wildlife habitat improvement. These activities can look very different from one another in terms of treatment design and implementation. For example, fuels-based treatments often do not consider the spatial variability and heterogeneity within stands and across the landscape that existed historically and are important for maintaining biodiversity, ecosystem functions and services, and resilience (Churchill et al. 2013b; Hessburg et al. 2015). Such treatments can result in stands with evenly spaced trees and lack of coarse wood and other features important for wildlife (Churchill et al. 2013b; Hessburg et al. 2015). An approach that identifies where different management goals are mutually beneficial and that integrates a range of treatment objectives—from fuels reduction to wildlife habitat enhancement to resilience—is needed for the Front Range.

Information specific to the Front Range—Much of the information guiding restoration on the Front Range comes from other areas of the western United States where dry coniferous forests occur, such as the Southwest (Reynolds et al. 2013), the Sierra Nevada (North et al. 2009), the Northern Rockies (Crist et al. 2009), and the Pacific Northwest (Franklin et al. 2013; Stine et al. 2014). Although information from other parts of the range of dry forest types is useful and important, most scientists and managers recognize the need for place-based restoration that incorporates local ecology and natural processes (Brown et al. 2004; Romme 2005; Schoennagel et al. 2004; Veblen 2003; Veblen et al. 2012) (panel 1). As described by Kaufmann et al. (2005: p. 483), "relatively subtle differences in ponderosa pine stand development exist across the geographic range of the species, but in combination with physical site characteristics and weather, significant contrasts exist in fire behavior patterns and assemblages of stands into a landscape structure."

Restoration within a mixed-severity fire regime—Much of the Front Range is characterized by a mixed-severity fire regime, with low-, moderate-, and high-severity

Panel 1—Important Characteristics of the Front Range Relative to Other Regions of the Western United States

- The **climate of the Front Range is relatively dry**, with precipitation typically averaging 10 to 20 inches per year (Veblen and Donnegan 2005).
- **Soils tend to be shallow** and are very heterogeneous, with montane hillslopes dominated by immature, rocky, coarse-textured, slightly acidic soils, with relatively low moisture-holding capacity (Peet 1981).
- Together, **climate and soils lead to fairly poor site quality and growing conditions** in many areas. Site indices for ponderosa pine range from 40 to 65 feet (base age 100) along the Front Range and are generally lower than other regions where ponderosa pine and dry mixed-conifer forests occur, such as the Black Hills (range of about 40 to 80 feet) and the Southwest (range of 40 to 100 feet) (Alexander 1986; Keyser and Dixon 2008; Schubert 1974; Shepperd and Battaglia 2002).
- **Ponderosa pine recruitment is highly episodic** on the Front Range and depends on both a good cone crop and favorable moisture conditions for germination and establishment (League and Veblen 2006; Mast et al. 1998; Mooney et al. 2011; Rother and Veblen 2016; Shepperd et al. 2006). In addition to the "safe-site" mechanism described for tree regeneration in frequent-fire landscapes (Larson and Churchill 2012), a "safe period" may be important for the Front Range (Huckaby et al. 2001). It may take longer for seedlings to reach a fire-resistant size, as well as to develop into ladder fuels, on the Front Range compared to other areas of the western United States.
- The highly dissected topography of the Front Range creates variability in productivity and fuel accumulation. This variability in fuels and topography, in turn, tends to promote a **mixed-severity fire regime**, with areas of both low-severity and moderate- to high-severity fire (Baker et al. 2007; Brown et al. 1999; Kaufmann et al. 2006; Noss et al. 2006; Romme et al. 2003b; Schoennagel et al. 2004; Sherriff et al. 2014; Veblen et al. 2012; Williams and Baker 2012b). This mixed-severity fire regime, where patches of crown fire and tree mortality were not uncommon historically, is one of the key distinctions between the Front Range and other areas such as the Southwest, and should be an emphasis of restoration work. Some level of high-severity fire should be accepted (and even considered desirable) within the larger landscape restoration context (Hutto et al. 2016).
- Because of lower productivity, **fuels may accumulate more slowly** on the Front Range compared to other, more productive ponderosa pine forests in the western United States. (Hunter et al. 2007; Kaufmann et al. 2005; Robertson and Bowser 1999). Slower rates of fuel accumulation may also be partially responsible for the longer recorded historical fire return interval on the Front Range compared to other areas (Baker et al. 2007; Kaufmann et al. 2006; Laven et al. 1980).
- Together, lower productivity, fuels accumulation, and episodic tree recruitment may translate to **longer treatment effectiveness** on the Front Range than other areas. Maintenance treatments may need to occur every 10 years in more productive areas such as the Southwest or Black Hills (Battaglia et al. 2008), but only every 15 to 20 years in less productive areas of the Front Range (Hunter et al. 2007). The schedule and return interval for maintenance treatments, however, are highly dependent upon site productivity and are likely to be shorter for more productive sites compared to less productive sites.

fire effects all having occurred historically on the Front Range, depending on factors such as elevation and slope (Brown et al. 1999; Kaufmann et al. 2006; Sherriff et al. 2014; Williams and Baker 2012b). The low-severity, frequent fire model developed for the southwestern United States applies only to portions of the Front Range, where landscape and stand structure patterns support surface fire and inhibit high-intensity crown fire. Ideally, restoration would be aimed at restoring a range of fire severities consistent with historical dynamics, yet implementing high-intensity fire through prescribed fire is challenging on the Front Range due to social perceptions and safety concerns. Thus, areas historically characterized by a predominantly low- and moderate-severity fire regime represent the highest priority for restoration, through mechanical treatment and reintroduction of low-intensity, prescribed surface fire. For high-severity components of the natural fire regime, we will undoubtedly continue to experience wildfire on the Front Range that will result in high-severity fire effects, but the challenge lies in identifying where those fire effects can occur without placing ecological and human values at significant risk.

Desired conditions—Desired conditions are central to the restoration process as they serve as a clear benchmark for measuring restoration progress and success. Developing desired conditions for Front Range forests has proven difficult, however, due to uncertainties about the HRV in forest structures, composition, and spatial heterogeneity to be used as benchmarks for restoration at specific sites and across larger landscapes. Desired conditions must be amenable to change as new science is developed and lessons are learned through monitoring and adaptive management. Developing desired conditions that will improve forest resilience, protect values at risk, and enhance ecosystem services in light of climate change and an expanding wildland-urban interface is a challenge but is needed.

Planning and prioritizing treatments—Funding is limited for vegetation treatments, so a strategic planning approach should be taken to maximize treatment benefits, effectiveness, and longevity. Yet questions remain about treatment prioritization. A framework for landscape evaluation and planning is needed that addresses questions such as: What areas on the landscape are most important to treat to achieve maximum benefit, and how much of the landscape needs to be treated to achieve meaningful ecological outcomes?

Treatment design and implementation—Treatment design criteria need to consider ecological dynamics and the environmental factors shaping forest structure and composition across scales. Ecological dynamics can be very complex, and the available science needs to be accessible and relevant to forest management. Ultimately this information must be useful in guiding what treatments should “look like” for a given project area based on physiographic settings, disturbance regimes, and forest developmental processes.

Climate change—The climate of Colorado is changing. Temperatures have increased by an average of 2.0 °F in the last 30 years, the timing of snowmelt and runoff has shifted 1 to 4 weeks earlier in the spring, and longer fire seasons with more land area burned are expected as well (Litschert et al. 2012; Lukas et al. 2014). Considering these changes, what can managers do on the ground to promote long-term forest resilience? Although much uncertainty frames the dialogue about climate mitigation for the Front Range, development of a general set of “climate-informed” restoration practices is needed. Restoration goals adopted today must be forward-looking and appropriate to future climatic conditions.

1.4 Purpose and Goals

This document builds on previously published reports that describe historical fire regimes and the HRV in structure and composition for Front Range forests (Aplet et al. 2014; Dickinson and SHSFRR 2014; Kaufmann et al. 2006; Veblen and Donnegan 2005).

The purpose of this document is to develop science-based guidance for ecological restoration of ponderosa pine and dry mixed-conifer forests and woodlands of the Colorado Front Range. Specific goals of this document are to:

- Provide an efficient **summary of the scientific information** most relevant to restoration of ponderosa pine and dry mixed-conifer forests of the Front Range, drawing on important published synthesis papers for Front Range forest and fire science;
- Establish a common understanding of the **factors influencing forest conditions at multiple scales**, in sufficient detail to move toward meaningful desired conditions, objectives, and management prescriptions;
- Define a **broad set of principles** that frame the approach to forest restoration, highlighting the need to incorporate variability in forest structure and composition as a result of environmental gradients, natural disturbances, and forest developmental processes, as well as to incorporate climate change implications, in treatment planning and implementation;
- Serve as a tool to help facilitate the **consistent application of restoration principles** across agencies, organizations, and private landowners engaged in forest restoration activities on the Front Range;
- Provide **a framework for planning and designing restoration projects across scales** to help managers identify priority areas for treatment at the landscape scale, as well as to guide the development of design criteria at the treatment scale;
- **Highlight information gaps** that may lead to the development of future research questions and projects; and
- Serve as a resource for **collaborative forest restoration** across multiple land ownerships, agencies, and organizations by engaging multiple disciplines in the planning, design, and implementation of restoration projects on the Front Range.

1.5 Intended Audience, Organization, and Overview

This document was developed by a team of scientists and managers who have been engaged in forest restoration on the Colorado Front Range through the Front Range Roundtable and the Collaborative Forest Landscape Restoration Program. The intended audience of this document includes planners and practitioners from Federal, State, and local agencies, as well as environmental nongovernmental organizations, working on both public and private lands on the Front Range. Resource specialists, managers, and line officers with the Forest Service, U.S. Department of Agriculture, and other Federal and State agencies are key audiences for this document, as are practitioners who work with private landowners. Additionally, we hope this document has relevance to the broad range of stakeholders involved in discussions of forest policy, as well as residents and visitors who use and enjoy Front Range forests.

Our goal in this document is to foster an all-lands approach by providing guidance applicable to a wide range of disciplines and end-users. Although our geographic focus is confined to the Colorado Front Range, we believe the principles described in this document, as well as the general framework provided for implementation, are relevant to a wide audience throughout the western United States.

This document is meant to provide a logical flow of information, organized by the following broad sections: (1) Background, (2) Principles and Guidelines for Restoration, (3) Principles to Practice—A Process for Restoration at Landscape and Stand Scales, (4) Additional Considerations for Front Range Forest Restoration, and (5) Information Needs.

- **Background—**This section provides background about Front Range ponderosa pine and dry mixed-conifer forest types, including forest settings, historical dynamics, and important ecological changes since Euro-American settlement of the Front Range that set the stage for restoration.
- **Principles and Guidelines for Restoration—**This section describes restoration principles and guidelines based on science relevant to Front Range forests. This section highlights important interactions among topography, natural disturbances, and forest developmental processes that shape forest structure and composition across different scales on the Front Range, and emphasizes the need to adopt forward-looking management practices in the context of climate change. Additionally, this section emphasizes the importance of adopting and adhering to an adaptive management process to guide the planning, implementation, and monitoring of restoration projects.
- **Principles to Practice—A Process For Restoration at Landscape and Stand Scales—**This section provides an implementation framework intended to facilitate on-the-ground application of restoration principles at multiple scales. This section is organized as a stepwise process that incorporates the following themes: identification of restoration goals and desired conditions, assessments to prioritize treatment areas, development of treatment plans and prescriptions, and monitoring and adaptive management.
- **Additional Considerations for Front Range Forest Restoration—**This section provides additional guidance for the practical application of the concepts in this document, including the value of interdisciplinary team approaches to restoration; tips for compartmentalizing the Front Range for assessments; and guidance for building and sustaining collaborative partnerships to strategically prioritize and implement forest restoration.
- **Information Needs—**This section identifies important information needs that should be addressed through research to continue to advance restoration efforts on the Front Range.

Throughout this document, we use nontechnical terms such as “steep slope” and “north-facing.” These terms are defined in table 2. This report is not intended to provide all the answers to forest management on the Front Range, but rather is meant to serve as a foundation upon which managers can build scientifically sound forest restoration across Front Range landscapes. Additionally, we hope this report will facilitate collaboration and public involvement in the forest restoration planning and implementation process.

Despite the best available science, unknowns still characterize restoration in Front Range landscapes. We expect that scientific knowledge and management practices will continue to evolve, and we encourage practitioners to continually incorporate new knowledge into treatment approaches. We also emphasize the importance of experimentation and innovation in management strategies, and the need to incorporate monitoring and adaptive management as a means of learning while doing. Forest restoration on the Front Range is in many ways an experiment and should include the explicit development of hypotheses that can be tested through ecological monitoring and research. As new science is developed and practical lessons are learned, this document should be updated to keep it relevant to Front Range land managers and scientists.

Table 2—Definitions of common terms used in this document.

Term	Definition
Southern Front Range	Area of Front Range south of Interstate 70
Northern Front Range	Area of Front Range north of Interstate 70
Lower montane	Elevational position below approximately 8,200 feet on the southern Front Range and 7,800 feet on the northern Front Range
Upper montane	Elevational position approximately 8,200 to 9,300 feet on the southern Front Range and 7,800 to 9,100 feet on the northern Front Range
South aspect	A slope that faces in a southerly direction, between 135° and 225° azimuth
North aspect	A slope that faces in a northerly direction, between 315° and 45° azimuth
Low density	Forested areas with canopy cover between 10 and 40 percent
Medium density	Forested areas with canopy cover between 41 and 70 percent
High density	Forested areas with more than 70-percent canopy cover
Steep slope	Slopes that are greater than 40 percent
Shallow slope	Slopes that are less than 20 percent

2. Background

2.1 Front Range Forest Setting

The Front Range represents the easternmost terminus of the Rocky Mountains and the junction between the Rocky Mountain and Great Plains physiographic provinces (Fenneman 1931). Elevation ranges from about 5,000 feet on the plains to more than 14,000 feet at the crests of some of the taller peaks, such as Longs Peak and Pikes Peak. Vegetation changes dramatically over this elevational gradient, reflecting the variation in environmental conditions that occurs with elevation (fig. 3). As stated by Daubenmire (1943: p. 326), "On approaching the Rocky Mountains, even the most casual observer cannot fail to be impressed by the sudden change in vegetation where the forest-covered mountain slopes rise abruptly from the unforested basal plain." As the Front Range rises from the plains, scattered ponderosa pine begins to occur within an elevational range of 5,600 to 6,000 feet in what Marr (1961) calls the grassland-lower montane ecotone. Ponderosa pine becomes more frequent with increasing elevation in the lower montane from roughly 6,000 to 7,700 feet and co-occurs with Douglas-fir (*Pseudotsuga menziesii*), especially in areas with higher soil-moisture content such as on north-facing slopes (Romme et al. 2003b) (fig. 4). Rocky Mountain juniper (*Juniperus scopulorum*) is another common associate, particularly on dry sites. Gambel oak (*Quercus gambelii*) is often present in the southern Front Range, south of Interstate 70. Fire-maintained ponderosa pine stands are generally open and characterized by a graminoid, forb, and shrub understory. Dominant graminoids include blue grama (*Bouteloua gracilis*), mountain muhly (*Muhlenbergia montana*), little bluestem (*Schizachyrium scoparium*), spike fescue (*Leucopoa kingii*), Ross' sedge (*Carex rossii*), and Geyer's sedge (*Carex geyeri*)

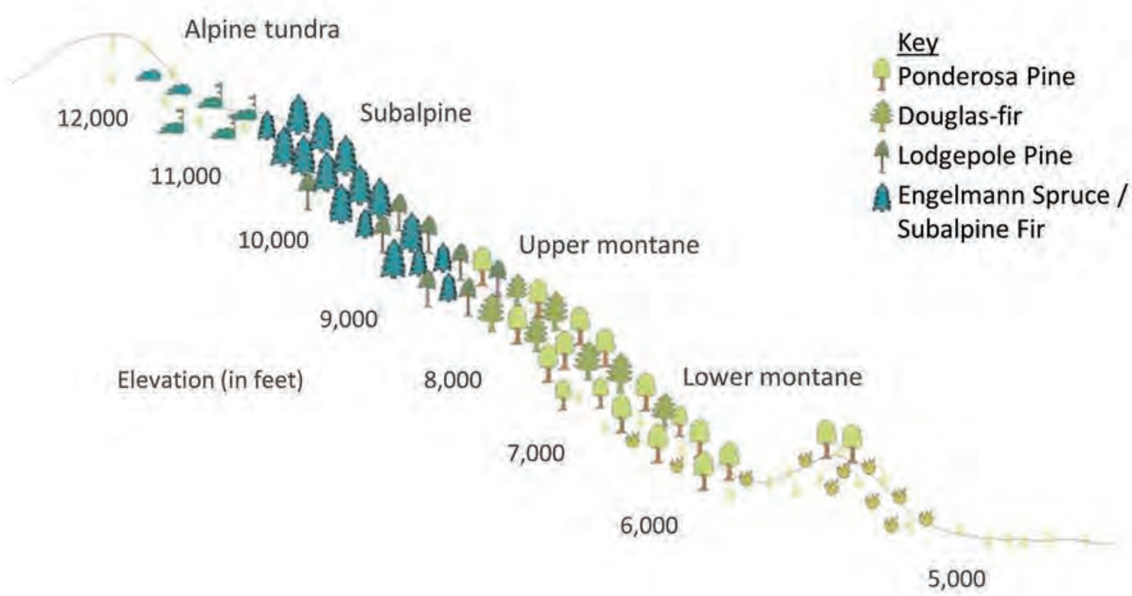

Figure 3—General change in vegetation with elevation on the Front Range. Ponderosa pine and dry mixed-conifer forests and woodlands typically occur in the lower and upper montane zones within an elevational range of about 5,500 to 9,200 feet (figure adapted from Huckaby et al. 2003b, with permission).

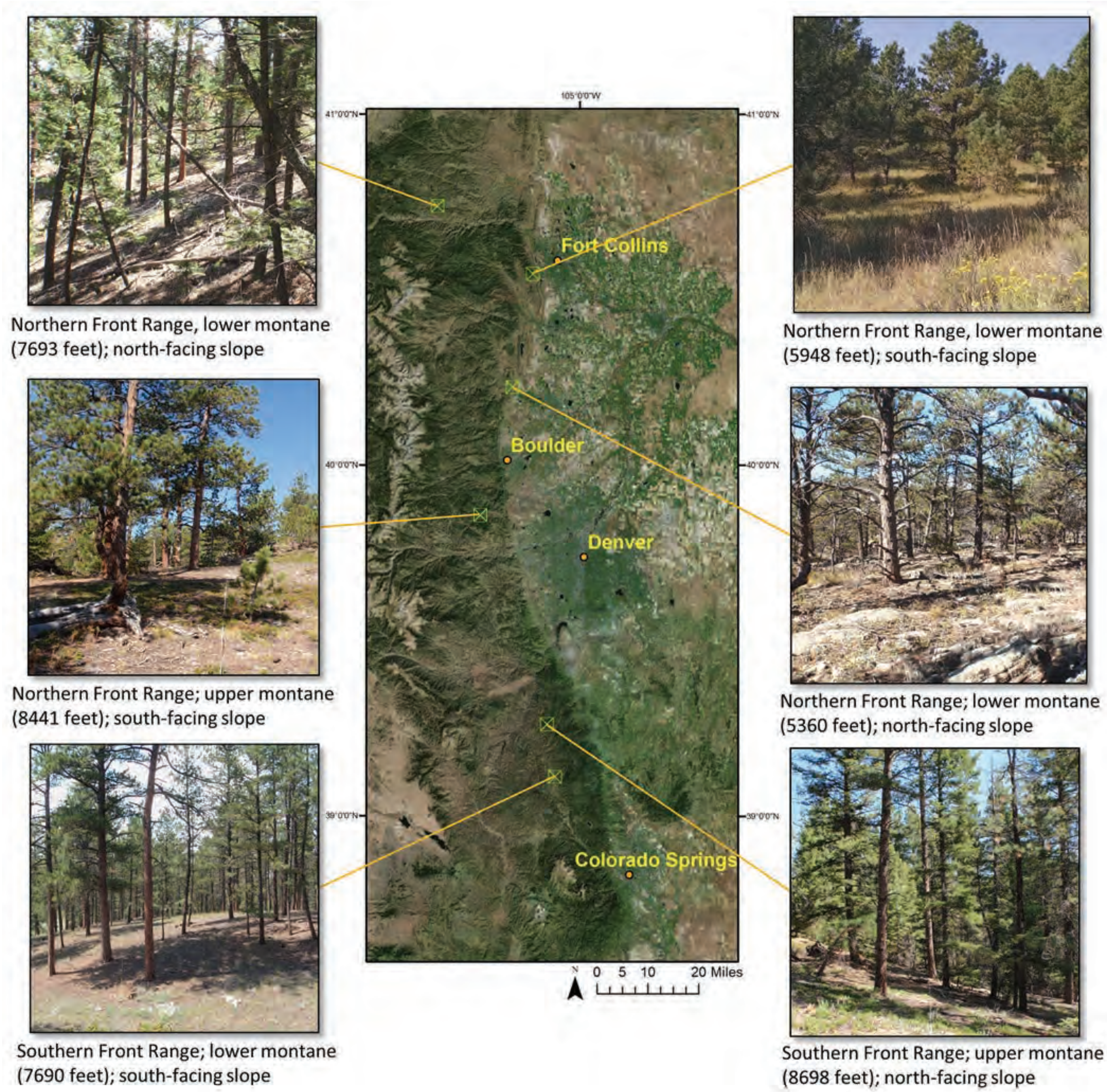

Figure 4—Variation in current structure and composition of ponderosa pine and dry mixed-conifer forests along the Front Range.

(Marr 1961; Peet 1981). Species typically associated with tallgrass prairie (e.g., bluestem grasses: *Andropogon* spp.) also occur throughout the lower montane zone. Mountain mahogany (*Cercocarpus montanus*), skunkbrush (*Rhus trilobata*), buckbrush (*Ceanothus fendleri*), wax currant (*Ribes cereum*), and antelope bitterbrush (*Purshia tridentata*) often make up the shrub component of ponderosa pine ecosystems, with common juniper (*Juniperus communis*) and kinnikinnick (*Arctostaphylos uva-ursi*) also prevalent as groundcover woody plants (table 3).

Ponderosa pine forests grade into dry mixed-conifer forests as the proportion of other conifers such as Douglas-fir increases, typically with increases in moisture availability (fig. 5). More mesic conditions associated with increases in elevation and north-facing

Table 3—Vegetation associated with ponderosa pine and dry mixed-conifer forests and woodlands in the Front Range, compiled from the Colorado Natural Heritage Program (2005), Fornwalt et al. (2009), Johnston (1987), Peet (1981), the Southwest Regional Gap Analysis Project (Prior-Magee et al. 2007), and LANDFIRE (Rollins 2009).

Ecological system	Common tree species	Common understory species
Southern Rocky Mountain Ponderosa Pine Woodland	Ponderosa pine, Douglas-fir, Rocky Mountain juniper, Gambel oak (southern Front Range)	**Graminoids—**blue grama, mountain muhly, little bluestem, spike fescue, Ross' sedge, Geyer's sedge, bluestem grasses **Forbs—**fringed sage (*Artemisia frigida*), white sagebrush (*Artemisia ludoviciana*), pineywoods geranium (*Geranium caespitosum*), hairy false goldenaster (*Heterotheca villosa*), prairie bluebells (*Mertensia lanceolata*) **Shrubs—**mountain mahogany, skunkbrush, buckbrush, wax currant, antelope bitterbrush, common juniper, kinnikinnick
Rocky Mountain Dry-Mesic Montane Mixed-Conifer Forest and Woodland	Ponderosa pine, Douglas-fir, limber pine, lodgepole pine, blue spruce, aspen, white fir (southern Front Range)	**Graminoids—**Arizona fescue (*Festuca arizonica*), mountain muhly (*Muhlenbergia montana*), Ross's sedge (*Carex rossii*), prairie Junegrass (*Koeleria macrantha*) **Forbs—**small-leaf pussytoes (*Antennaria parvifolia*), Virginia strawberry (*Fragaria virginiana*), pineywoods geranium (*Geranium caespitosum*), prairie bluebells, Mt. Albert goldenrod (*Solidago simplex*) **Shrubs—**Oregon grape, mountain mahogany, wax currant, common juniper, kinnikinnick, mountain snowberry (*Symphoricarpos oreophilus*), cliffbush

slopes support dry mixed-conifer forests (Peet 1981). Dry mixed-conifer forests are similar to ponderosa pine forests in overall character, but differ somewhat in species composition and productivity. Douglas-fir and ponderosa pine typically still make up most of the basal area, but limber pine (*Pinus flexilis*), lodgepole pine (*Pinus contorta*), blue spruce (*Picea pungens*), and aspen (*Populus tremuloides*) are often present as well (Peet 1981). White fir (*Abies concolor*) may be present in the southern Front Range. Productivity is generally higher in dry mixed-conifer compared to ponderosa pine forests, and thus stands are characterized by higher overstory canopy cover and greater species and age diversity; these stands concurrently lack the abundant herbaceous understory characteristic of open-canopied forests, unless frequently burned (Keith et al. 2010; Peet 1981). As in ponderosa pine forests, several species of shrubs can also be found in dry mixed-conifer forests, including wax currant, mountain mahogany, kinnikinnick, common juniper, and cliffbush (*Jamesia americana*) (Marr 1961; Peet 1981). Dry mixed-conifer forests extend above 9,000 feet in many areas of the Front Range, though they give way to wet mixed-conifer forests as moisture availability increases with elevation or aspect (Peet 1981). Species such as lodgepole pine and Engelmann spruce (*Picea engelmannii*) accompany the transition to wet mixed-conifer forests, typically above 8,000 feet. Similarly, ponderosa pine is often present at higher elevations but begins to drop out as the forest further gives way to dry mixed-conifer and wet mixed-conifer, lodgepole pine, and subalpine forest types above 9,000 feet, and alpine tundra at about 11,500 feet.

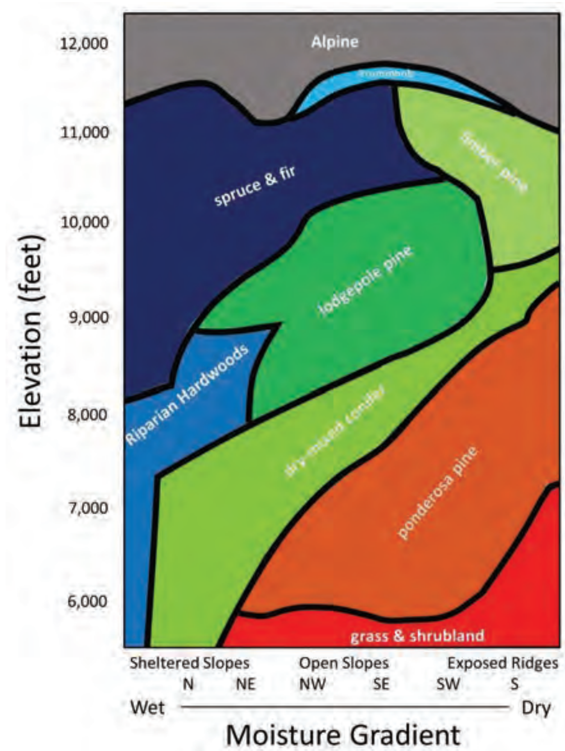

Figure 5—Dominant forest types by elevation and topographic position on the northern Front Range (adapted from Peet 1981, with permission).

2.2 Then and Now: Important Ecological Changes in Front Range Forests

Understanding historical ecological dynamics is important for present-day forest management, as history provides us with a sense of how forests have changed through time and the range of ecological features that were present historically but may be missing today. For Front Range ponderosa pine and dry mixed-conifer forests, ecological change and departure from historical conditions have been most pronounced in the lower montane (FRFTPR 2006; Kaufmann et al. 2006; Platt and Schoennagel 2009; Sherriff et al. 2014; Veblen and Donnegan 2005). These forests were heavily influenced by Euro-American settlement beginning in the 1850s (Binkley and Duncan 2009; Colorado State Forest Service 2009; Romme et al. 2003b; Veblen and Donnegan 2005; Veblen and Lorenz 1991). The combined effects of logging, grazing, fire setting, and fire exclusion since the settlement period have dramatically changed the character of Front Range ponderosa pine and dry mixed-conifer forests. In this section, we highlight general ecological changes that have occurred in these forests, based on the available science, to provide a foundation for restoration.

2.2.1 Forest Density

Numerous studies suggest that forest density has increased in many areas of the Front Range, particularly in lower montane settings (Brown et al. 2015; Fornwalt et al. 2002; Kaufmann et al. 2000, 2003; Mast et al. 1997; Platt and Schoennagel 2009; Sherriff and Veblen 2006; Veblen and Donnegan 2005; Veblen and Lorenz 1991). This increase in forest density is believed to be a result of favorable conditions for tree establishment created by logging, grazing, fire exclusion, and climatic conditions through much of the 20th century (Romme et al. 2003b; Sherriff and Veblen 2006; Veblen and Lorenz 1991). High forest density creates a continuous, uniform canopy condition that can facilitate the unimpeded spread of high-severity fire and insect outbreaks. Further, it supports favorable conditions for shade-tolerant species such as Douglas-fir to recruit at higher densities, which can increase ladder fuel development, lower crown base heights, and create vertical canopy continuity (Fulé et al. 2004). It is important to note, however, that the Front Range was historically characterized by a wide range of forest densities and that not all high-density stands are outside of the HRV (Brown et al. 2015; Platt and Schoennagel 2009; Sherriff and Veblen 2006; Veblen and Donnegan 2005; Williams and Baker 2012b). In the upper montane in particular, stand density naturally increases as dry coniferous forests give way to wet mixed-conifer and lodgepine pine forests. Dense stands in these settings are probably a product of several interacting factors, including recovery from widespread 19th-century fires that coincided with warm-dry episodes on the Front Range and throughout the Rockies (Kitzberger et al. 2007; Schoennagel et al. 2011; Sherriff and Veblen 2006).

2.2.2 Openings

Openings are areas within the forest matrix that contain few to no trees. In this document, we distinguish between two types of openings: openings that are relatively persistent on the landscape (e.g., meadows) and openings that are more transient and provide opportunity for tree regeneration. Persistent openings are often underlain by Mollisol soils (Abella et al. 2013; Peet 1981) and contain an abundant herbaceous vegetation layer that supports surface fire and inhibits tree regeneration. Persistent openings may occur as well on dry sites that are underlain by Inceptisols (well-drained soils with minimal horizon development) and that do not support tree cover due to unfavorable conditions for tree establishment. Transient openings are areas that once contained trees but lost tree cover due to disturbances such as high-severity fire or insect outbreaks (Brown et al. 1999; Kaufmann et al. 2000; Williams and Baker 2012a). Transient openings provide sites for tree regeneration and are important for perpetuating variable-aged stand conditions and contributing to the shifting mosaic characteristic of fire-dependent ecosystems, whereby regeneration patches shift on the landscape both spatially and temporally. Openings in general are believed to have been more prevalent historically in ponderosa pine and dry mixed-conifer forests on the Front Range than they are currently, due to tree infill that can occur with fire exclusion (Dickinson 2014; Huckaby et al. 2001; Kaufmann et al. 2000, 2003). This is especially true for small openings (openings <165 feet long; Dickinson 2014). Both persistent and transient openings provide important ecosystem functions, including opportunity for understory herbaceous and shrub community development (Kovacic et al. 1985; Matonis 2015; Mitchell and Bartling 1991), as well as habitat for wildlife. Openings also contribute to overall landscape heterogeneity and provide natural barriers to the broad-scale spread of high-severity and stand-replacing disturbances (Turner et al. 2013).

2.2.3 Heterogeneity at Landscape and Stand Scales

Complex interactions among topography, climate, and fire historically created a rich landscape mosaic in ponderosa pine and dry mixed-conifer forests on the Front Range.

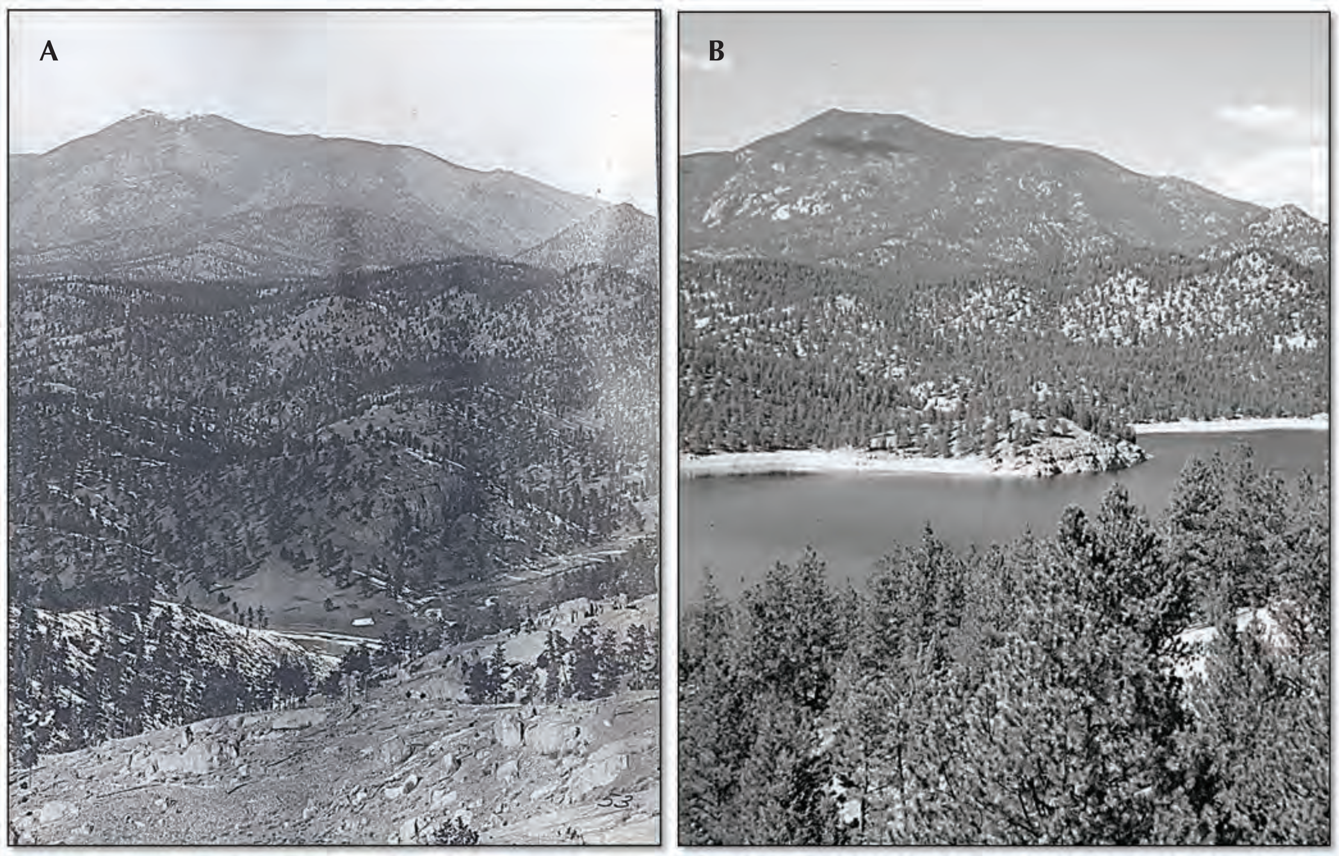

Figure 6—Paired historical and current photographs of the Cheesman Reservoir landscape illustrating the general increase in forest density, loss of openings, and diminished landscape mosaic that occurred from (a) 1896 to (b) 2000 (photo (a): Denver Water, used with permission; photo (b): M. Kaufmann, U.S. Forest Service).

Uneven-aged, old-growth forests maintained by frequent low-severity fire intermixed historically with mid-successional forest patches, as well as transient openings created by stand-replacing fire (fig. 6) (Kaufmann et al. 2006; Romme et al. 2003a). At finer scales, such as individual forest stands, diverse patterns in forest structure were historically maintained by fine-scale (<1 acre) forest demographic processes, such as mortality of individual trees and tree groups, and stochastic tree recruitment. The "groupy-clumpy" stand structure, where trees occur in groups separated by transient openings (at a scale <1 acre), is characteristic of frequently burned forests (Larson and Churchill 2012). Heterogeneity at both landscape and stand scales has been diminished with fire exclusion, as tree infill occurs. This heterogeneous structure across scales is important for wildlife, native understory plant community abundance and diversity, and facilitation of low- and moderate-severity disturbances (Franklin et al. 2013; Larson and Churchill 2012).

2.2.4 Old Trees and Old-Growth Forests

Old trees and old-growth forests are vital components of landscape structural complexity and provide many important ecosystem functions, especially for wildlife (Binkley et al. 2007; Franklin 1989; Franklin and Johnson 2012; Huckaby et al. 2003a; Kaufmann et al. 2000, 2007; Kolb et al. 2007). Old trees and old-growth forests are believed to be less prevalent on the Front Range landscape currently than they were historically (Huckaby et al. 2001; Kaufmann et al. 2000, 2003; Veblen and Donnegan

2005). Loss of old trees and old-growth stands due to large-scale, high-severity, and stand-replacing fire is a concern among Front Range land managers and researchers. Much of the old-growth forest within the Cheesman Reservoir landscape of the Pike National Forest, for example, was lost in the Hayman Fire (Fornwalt et al. 2016).

2.2.5 Species Composition

Several studies suggest that there has been an increase in more shade-tolerant species such as Douglas-fir accompanying the overall increase in forest density and exclusion of fire, primarily in the lower montane zone (Brown et al. 2015; Hadley 1994; Huckaby et al. 2001; Kaufmann et al. 2000; Peet 1981). However, the extent to which Douglas-fir has increased in proportion to ponderosa pine is site-dependent (Schoennagel et al. 2011; Sherriff and Veblen 2006; Veblen and Lorenz 1986). The growth-form of shade-tolerant species (long crowns with branches often extended to the ground) like Douglas-fir increases the potential for fire spread into the tree canopy (Fulé et al. 2004).

2.2.6 Fire Regimes

The relatively frequent, low- and moderate-severity components of the mixed-severity fire regime that historically characterized ponderosa pine and dry mixed-conifer forests of the Front Range are largely absent from the landscape today, due in part to active fire suppression. Fire suppression tends to be most successful in combatting low-intensity surface fire, whereas high-intensity fires are more likely to escape suppression and result in high-severity fire effects (fig. 7). Although there is debate about the historical prevalence and role of large, high-severity fire in dry forest types of the western United States (e.g., Fulé et al. 2014; Williams and Baker 2014), most researchers and practitioners agree that fires that burn at predominantly low severity are less common today than historically. Loss of low-severity, frequent surface fire represents loss of a keystone ecological process responsible for shaping the structure and composition of Front Range forests.

Figure 7—High-severity fire effects within the 2012 High Park Fire (photo: B. Wudtke, Colorado Forest Restoration Institute, used with permission).

2.2.7 Fire Effects

Historical fire along the Front Range was highly variable in size and severity and was responsible for sustaining the diverse landscape mosaic believed to characterize the Front Range historically (Brown et al. 1999; Kaufmann et al. 2006; Romme et al. 2003a; Sherriff et al. 2014). Recent fires with very large stand-replacing patches that have occurred on the Front Range have resulted in relatively uniform fire effects over large areas. The Hayman Fire, for example, created large swaths of complete tree mortality (up to ~60,000 acres; Finney et al. 2003) that are likely to remain in a nonforested state for centuries based on the regeneration dynamics of ponderosa pine (Chambers et al. 2016; Rother and Veblen 2016). Ecological impacts from such large burn patches often include increased soil erosion and peak runoff, reduced carbon sequestration, and loss of late-seral habitat for wildlife (Stephens et al. 2014). But benefits are associated with stand-replacing burn patches, including for some wildlife species (Hutto 2008; Hutto et al. 2016; Kotliar et al. 2003). Additionally, the potential for future stand-replacing fire in these areas is reduced for decades to come (Harvey et al. 2016; Stevens-Rumann et al. 2016).

2.2.8 Understory

Less is known about changes in understory vegetation communities since Euro-American settlement than about other ecological changes on the Front Range (although see Fornwalt et al. 2009), but presumably those species adapted to frequent fire have not benefited from the exclusion of fire (Abella and Fornwalt 2015; Fornwalt and Kaufmann 2014). Numerous studies throughout ponderosa pine and mixed-conifer forests in the western United States document relationships between overstory canopy cover or basal area and understory vegetation cover (Abella and Springer 2015; Kovacic et al. 1985; Laughlin et al. 2011; Mitchell and Bartling 1991; Peet 1981). Results from these studies suggest that as overstory trees become denser and canopy cover increases, understory vegetation cover typically decreases due to decreases in light availability and the accumulation of litter and duff that together suppress understory vegetation development. Understory vegetation has probably been influenced as well through competition by nonnative species introduced since Euro-American settlement. Understory vegetation is important for many reasons, including forage for insects, birds, and mammals, as well as for supporting important ecological processes such as surface fire and soil stability to reduce erosion.

2.2.9 Insects and Pathogens

The historical frequency and extent of outbreak populations of native insects is less readily determined from tree ring records and other sources than is the history of fire, but several Front Range reports have documented numerous epidemic outbreaks of the mountain pine beetle (*Dendroctonus ponderosae*), the Douglas-fir tussock moth (*Orgyia pseudotsugata*), and the western spruce budworm (*Choristoneura occidentalis*) in ponderosa pine and dry mixed-conifer forests over the past two centuries (e.g., McCambridge et al. 1982; Veblen and Donnegan 2005; Witcosky 2009; and references therein). Some evidence suggests the mountain pine beetle causes greater levels of mortality in dense forest conditions compared to more open conditions (Graham et al. 2016; Hood et al.

2016; Negrón and Popp 2004), and that outbreaks can occur at intervals of 2 to 10 decades within regions or stands, depending on numerous factors such as climate and host availability (Schmid and Amman 1992; Veblen and Donnegan 2005). Other pathogens in these forest types include dwarf mistletoe (*Arceuthobium vaginatum* subsp. *cryptopodum*) and many species-specific or widespread diseases of roots, bark, or leaves. These diseases are known to have affected all coniferous and deciduous species throughout many centuries in this region, although little information is available on the extent and severity of their effects over time (Veblen and Donnegan 2005 and references therein).

2.2.10 Wildlife

Very little is known about how populations of wildlife species have changed since Euro-American settlement on the Front Range. Studies conducted in ponderosa pine forests throughout several western States have documented a range of responses to fire by wildlife, from positive to negative to neutral, depending on many aspects of the ecology, life history, habitat requirements, and trophic interactions of each species (Fontaine and Kennedy 2012; Hutto 2008; Hutto et al. 2016; Kalies et al. 2010; Reynolds et al. 1992; Saab and Powell 2005). On the Front Range, as elsewhere, it is likely that fauna dependent on frequent-fire habitats have not benefited from fire exclusion due to changes in plant community structure and composition (Pilliod et al. 2006). Within this landscape, species of concern for resource managers include the Pawnee montane skipper, northern goshawk (*Accipiter gentilis*), Mexican spotted owl (*Strix occidentalis lucida*), mule deer (*Odocoileus hemionus*), and Abert's squirrel (*Sciurus aberti*), as these species use food sources or habitat features that are typically maintained by characteristic fire patterns through time (Colorado State Forest Service 2009). Populations of numerous other species have undoubtedly been affected either negatively or positively by alterations of the characteristic fire regime. Although long-term datasets do not exist to quantify historical or recent relationships between wildlife species of concern and patterns of fire occurrence and severity in the Front Range, these relationships should be carefully considered using all sources of relevant information, and monitored when possible, in any future Front Range restoration treatment plans that will use or simulate the effects of fire.

3. Principles and Guidelines for Restoration

The ecological changes that have occurred for Front Range forests set the stage for restoration and provide a starting point for the development of restoration activities aimed generally at reducing forest densities and cover, increasing the size and frequency of openings, restoring the landscape mosaic, enhancing fine-scale (<1 acre) heterogeneity in tree spatial patterns, protecting and enhancing old-growth features and structural complexity, reestablishing a low- to mixed-severity fire regime where appropriate, and promoting long-term resilience in the face of climate change and future natural disturbance (Brown et al. 2015; Clement and Brown 2011; Dennis and Sturtevant 2007; FRFTPR 2006; Kaufmann et al. 2000, 2003; Veblen and Donnegan 2005). These broad restoration goals have been expressed in various forms by the Front Range restoration community through the years and are central to the restoration effort today.

The challenge for Front Range restoration now is moving beyond broad goals to on-the-ground restoration through planning and implementing restoration treatments. This part of the restoration process inherently requires some understanding of ecological dynamics and the complex factors shaping vegetation structure and composition on the landscape, including biophysical factors, natural disturbances, and forest developmental processes (fig. 8). In this section, we outline a broad set of principles that shape the

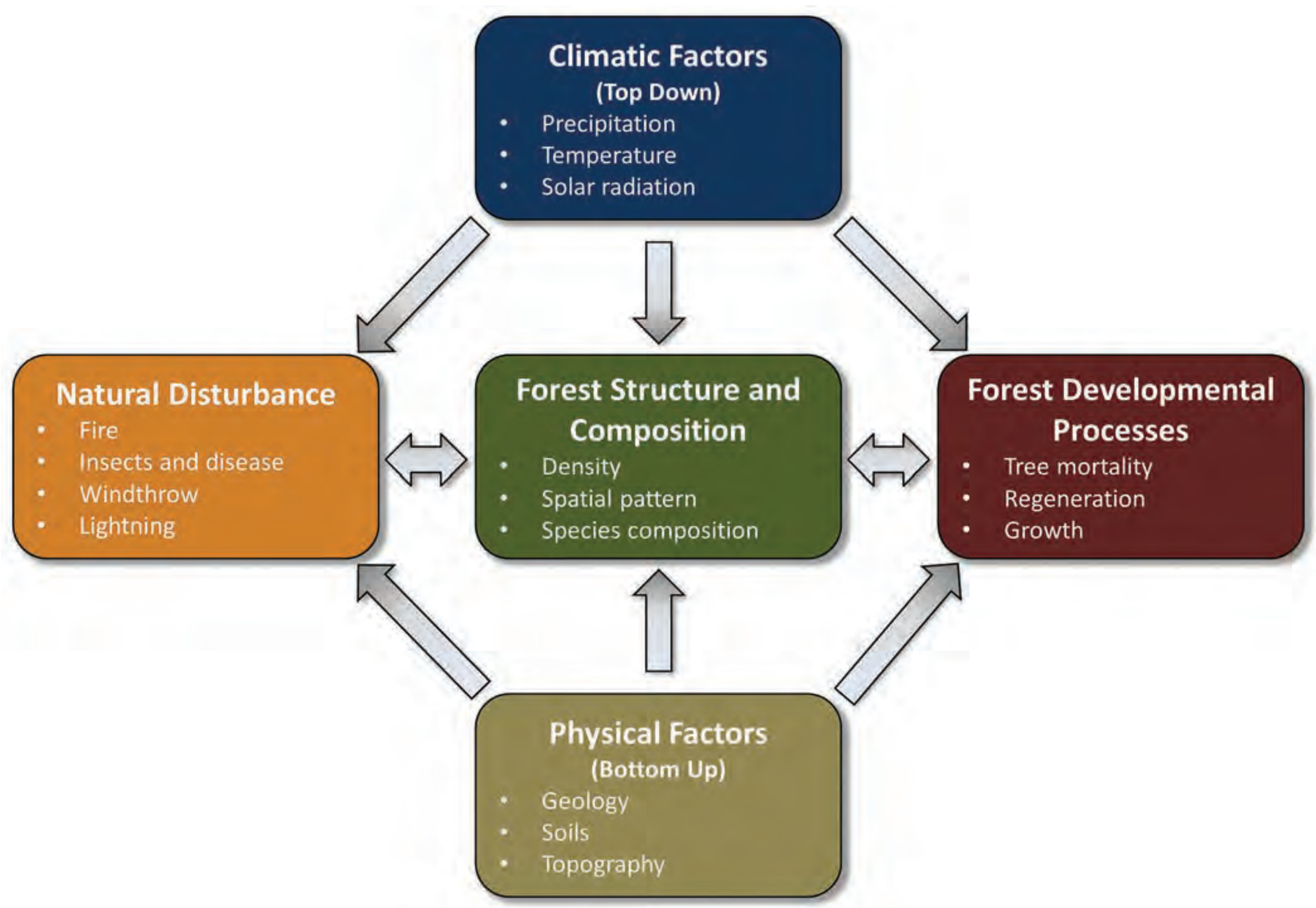

Figure 8—Generalized conceptual model illustrating interactions among climate, natural disturbance, forest developmental processes, and physical factors that influence forest structure and composition on the Front Range.

approach to Front Range forest restoration (panel 2), followed by guidelines that we believe are particularly relevant to the restoration process for Front Range forests, based on available scientific information. This information serves as a foundation for the planning and implementation stages of restoration discussed later in the document.

3.1 Restoration is Informed but not Constrained by the Historical Range of Variability

The concept of HRV has long provided an important basis for restoration work and should be considered a first principle for restoration of Front Range ponderosa pine and dry mixed-conifer forests. The HRV is the range of conditions and processes that characterized ecological systems historically; it describes how ecological systems operated—how they developed over space and time and how they responded to natural disturbances—before the introduction of new disturbance phenomena that occurred with Euro-American settlement (Aplet and Keeton 1999; Egan and Howell 2001; Harrod et al. 1999; Moore et al. 1999; Morgan et al. 1994; Romme et al. 2012; Veblen et al. 2012). Central to the concept of HRV is the notion that ecological systems are dynamic—not static—and are characterized by a complex range of conditions that can shift in time and space but are fundamentally self-sustaining (Hayward et al. 2012; Keane et al. 2009; Landres et al. 1999). Implicit in the HRV is the premise that ecological systems were resilient in structure and function to climatic fluctuations and natural disturbances historically, and therefore an understanding of the HRV can help to confer resilience in contemporary ecological systems.

For restoration of Front Range ponderosa pine and dry mixed-conifer forests, understanding the HRV is important for several reasons. First, the HRV provides planners and managers with a sense of how forest structure and composition varied with the diverse physiographic settings and natural disturbance regimes of the Front Range. Second, the HRV improves our understanding of where current forest conditions are most significantly departed from historical conditions, which helps in prioritizing where restoration should occur on the ground. Third, the HRV provides benchmarks or targets for the development of desired conditions to be achieved through management and natural disturbances, thereby shaping the overall management approach and informing treatment designs and prescriptions (Fulé et al. 1997; Harrod et al. 1999; Landres et al. 1999). Several valuable publications describing the HRV have been developed for Front Range forests, including Kaufmann et al. (2006), Romme et al. (2003a,b), Veblen and Donnegan (2005), and Veblen et al. (2012). We encourage readers to consult these publications for detailed descriptions of historical dynamics characteristic of Front Range forests. We relate many of the themes expressed in these documents in the following sections.

Beyond providing an important conceptual framework, the HRV can and should be empirically derived for individual landscapes and treatment areas to inform the restoration process (Hayward et al. 2012; Romme et al. 2012; Veblen 2003). We encourage planners and managers to gather as much historical information as possible for their landscapes and treatment areas, including photos (e.g., Veblen and Lorenz 1991) and historical written accounts (e.g., Jack 1900; see Appendix A). Employing on-the-ground techniques such as forensic forestry allows managers to infer historical site characteristics based on structural features that often still exist onsite and that can provide clues

Panel 2—General Principles for Front Range Forest Restoration

- **Front Range forests have changed throughout time** and it is important to acknowledge that they will continue to change. Our role as scientists and practitioners should be to guide that change in a way that we believe will sustain a wide range of important forest functions, values, and services.

- **Looking to historical dynamics and the historical range of variability (HRV) is important** because it provides us with a sense of how Front Range forests were structured and how processes such as fire and other disturbances maintained forest function over time.

- The HRV provides a valuable starting point for thinking about restoration goals and ecosystem desired conditions, but **it is important to be forward-looking in the context of climate change** and not constrained by the HRV. Rather, information from the past should be used as a guide to anticipate potential forest responses to future climate and disturbance factors.

- Although the future is uncertain, we know with some certainty that **fire will continue to occur as a natural ecological process**. Restoration should be aimed at restoring forest structure patterns necessary to facilitate a low-severity fire regime where ecologically appropriate, as well as identifying those areas where moderate- and high-severity fire can be allowed to occur naturally without significantly impacting ecological and human values.

- **Enhancing heterogeneity at multiple scales will provide more options for adaptation** under future climatic conditions (Seastedt et al. 2013; Seidl et al. 2016; Turner et al. 2013). Conserving and enhancing diversity is a logical approach in the face of uncertainty to increase the odds of ecosystem values persisting through future disturbance events. Managing for rare or missing elements at both landscape and stand scales is particularly important in this context.

- **Treatment approaches should be mindful of ecological dynamics**, including forest developmental processes and interactions with environmental factors and disturbance events. Ecological forestry (Franklin et al. 2007; Seymour and Hunter 1999), emulation forestry (Perera and Buse 2004), natural disturbance based management (NDBM; Drever et al. 2006), and management of forests as "complex adaptive systems" (Puettmann et al. 2008) are examples of management approaches useful for restoration.

- **The functional importance of forest structure patterns should be considered across scales** when planning and implementing restoration projects. Functional roles of fine-scale features such as tree groups and openings, as well as landscape-scale patterns and patch dynamics, are all important.

- **Limited resources require that we prioritize landscapes where multiple benefits are most likely achievable**, and prioritization should be based on a multi-scale planning approach that recognizes important interactions and linkages across scales. Treatments at the stand scale should be informed by the larger landscape context.

- **Collaboration plays an important role** in restoration planning and treatment design. Garnering the support of multiple stakeholders and gaining social acceptance for restoration activities, including mechanical treatments and prescribed fire, are vital to the restoration process.

- **Adaptive management provides a framework for dealing with uncertainty** that inherently characterizes the restoration process. Adaptive management emphasizes continual learning and refinement of management actions based on outcomes of previous management. Monitoring is another key component of the adaptive management process.

- **Experimentation and innovation will be required**, especially given uncertainty about climate change and future disturbance dynamics (Seidl et al. 2016). A culture of innovation for Front Range forest restoration should be promoted and rewarded.

Figure 9—Fire-scarred ponderosa pine tree. Presence of fire-scarred trees within a treatment unit indicates historical surface fire with low-severity fire effects (photo: P. Brown, Rocky Mountain Tree-Ring Research, used with permission).

about what the forest looked like before Euro-American settlement (Matonis et al. 2014; Wessels 2010). Old trees (>150 years old), fire-scarred trees, stumps, logs, and other remnant material are all very useful indicators of past forest structure and disturbance regimes (fig. 9). The presence of these features indicates that low-severity fire was very likely the dominant disturbance regime. Likewise, a lack of legacy features is informative, as it can indicate previous disturbances such as high-severity fire that removed these features (Ehle and Baker 2003; Romme et al. 2003a), or may indicate site conditions that historically did not support tree cover (e.g., tree encroachment within former openings).

Despite the utility of the HRV for current restoration work, it is also important to recognize that the goal of restoration is not strictly to re-create historical forest structure and composition per se, but rather to use historical information as a guide in determining those forest structures and processes that may be appropriate for given physiographic settings. It is important to be forward-looking in the context of climate change and social factors that may make the HRV less relevant to contemporary forest conditions (Binkley and Duncan 2009; Fulé 2008; Hiers et al. 2012; Romme et al. 2012; Seastedt et al. 2008; Turner et al. 2013). Scientists and practitioners are increasingly reframing the HRV as the desired range of variability or future range of variability (FRV), based on an understanding of how changes in climate and future disturbance regimes may influence forest structure (e.g., Hessburg et al. 2015; Keane et al. 2009; Stine et al. 2014). An understanding of both the HRV and the FRV is therefore important in determining those forest structures that can be achieved through management and that may be most resilient to future disturbance and other factors such as drought. As stated by Fulé (2008: p. 530), "Historical reference conditions remain useful to guide management because forests were historically resilient to drought, insect pathogens, and severe wildfire. Adaptation of reference information to future climates is logical: historical characteristics from lower, southerly, and drier sites may be increasingly relevant to higher, northerly, and currently wetter sites."

Similarly, we encourage Front Range planners and managers to consider the potential future range of variability based on modeled climate projections and accompanying changes in disturbance regimes and factors such as drought (discussed in section 3.9). Several recent synthesis publications provide useful information about anticipated climate-change effects and responses in forest ecosystems, including Clark et al. 2016, Funk et al. 2014, Lukas et al. 2014, Rocca et al. 2014, and Ryan and Vose 2012.

3.2 Spatial and Temporal Scale Provide an Important Organizational Framework for Restoration

Our perception of ecological variability is highly influenced by the spatial and temporal scale at which observations of ecological structure, composition, and function are made. To account for spatially dependent variability, traditional landscape ecology is careful to distinguish between the influence of both grain and extent. Grain is the area over which a single observation is made, such as a plot or pixel, whereas extent captures the larger area over which multiple observations are distributed (White and Walker 1997). For Front Range ponderosa pine and dry mixed-conifer forests, grain can be thought of as the fine-scale variation in tree density and dispersion that might be observed on a single acre of land (fig. 10). At this scale, tree density varies from low to high, and tree dispersion varies from uniform to highly aggregated (what is often referred to as "clumpy" or "groupy"). From acre to acre, tree density and dispersion will vary based on physiographic features and interactions with natural disturbances and forest developmental processes. These individual acres will then "roll up" to much larger areas (i.e., the "extent") to create patterns of tree density and dispersion at broader scales (fig. 11).

For restoration, it is important to consider cross-scalar relationships in vegetation patterns and recognize that actions at one scale influence outcomes at other scales. Treatment planning should consider spatial scale and can be organized by scale (fig. 12). We distinguish broadly between the landscape scale and the treatment scale, with strategic planning being a primary function at the landscape scale and implementation being the main function at the treatment scale (table 4). At the landscape scale, managers may wish to have more than one level of organization, depending on the geographic scope and restoration goals. For example, strategic planning on the Front Range can begin at a **broad landscape scale** (100,000 to 1,000,000+ acres) equivalent to a national forest or 4^{th} level watershed (Hydrological Unit Code 8 [HUC-8]). Planning at the broad landscape scale would be aimed at identifying smaller **local landscapes** (on the order of 1,000

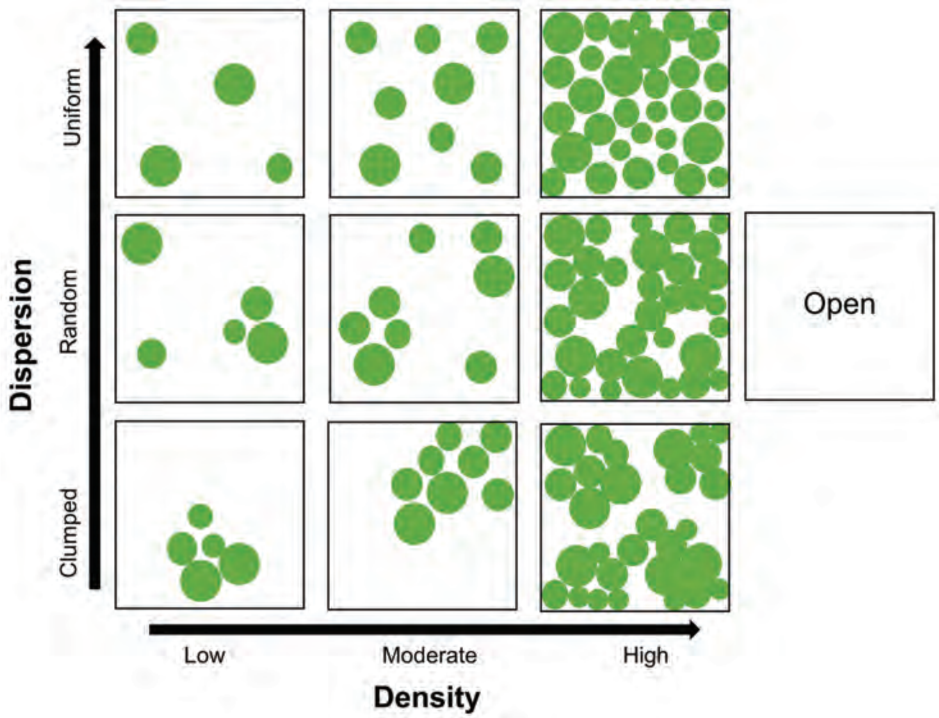

Figure 10—Hypothetical range of variation in fine-scale (<1 acre) tree density and dispersion. Tree density may range from low to high, depending largely on site productivity, fine-scale variation in moisture conditions, and disturbance history. Openings are a common feature at this scale as well. Variability in tree ages is represented by the different sized green dots, with larger dots representing older trees and smaller dots representing younger trees. The "groupy-clumpy" term used in the body of the text is best represented in the lower left of the diagram, under low-density forest conditions and clumped dispersion patterns.

to 100,000+ acres) where restoration efforts should be focused. Local landscapes are equivalent to one or several 6th level subwatersheds (HUC-12s) (Dickinson and SHSFRR 2014).

Strategic planning at the landscape scale will begin to point managers to progressively smaller scales where treatment implementation will occur. The main unit of organization at this scale is the **stand** or **treatment unit**. These areas are typically on the order of 1 to 100+ acres. On public lands, such as national forests, stands are often the primary unit of forest management and are defined as a contiguous group of trees uniform enough in age- and size-class distributions and species composition to be a distinguishable unit (Helms 1998). On private lands, stands often have not been delineated and therefore treatment units can be determined by property boundaries, terrain, roads, or operational boundaries, and may contain more than one forest type. Several stands or treatment units in proximity to one another may roll up to a **project area**, on the order of hundreds to 1,000+ acres (fig. 13).

The key point is that restoration planning and implementation follows a hierarchically structured process across spatial scales and recognizes important interactions and feedbacks that occur across scales (Hayward et al. 2012; Lindenmayer et al. 2008). Restoration should begin with a landscape-scale planning process that identifies high-priority treatment areas that, if treated, will advance landscape restoration goals. Treatment-scale planning should then be conducted within the landscape context. Treatment design should be informed by what is present on the landscape surrounding the

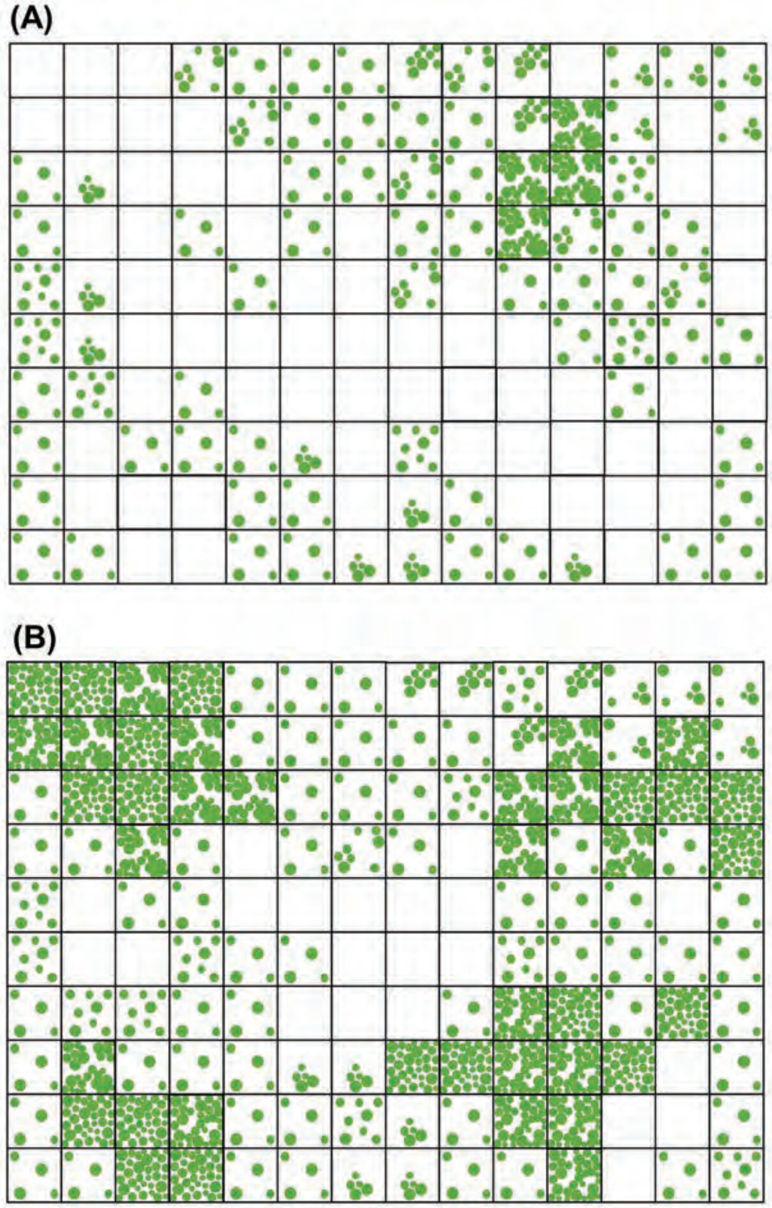

Figure 11—Hypothetical depiction of how variation at fine scales rolls up to create patterns at broader scales, driven largely by site environmental conditions and interactions with disturbance regimes: (a) open stand structure historically characteristic of low-severity frequent fire where fine-scale variation is characterized by individual trees, small groups of trees, and openings; (b) higher-density stand structure that may develop in areas with mixed-severity fire. The higher-density patches very likely represent areas of higher productivity, which may burn with moderate to high severity during dry conditions. More open areas may be maintained by low-severity surface fire, or may be recovering from high-severity fire that caused fine-scale patches of complete tree mortality. In both cases (a and b), fire exclusion would result in gradual infilling of low-density patches to create a higher-density forest condition with more uniform tree dispersion.

treatment unit. Treatments should enhance those rare or underrepresented features of the landscape we would expect to be present under an intact disturbance regime in order to enhance overall landscape heterogeneity.

A main concern with current Front Range forests is the way in which forest recovery from settlement-era disturbances has aligned in both space and time to create relatively uniform forest conditions in many areas. Beyond spatial considerations, restoration should recognize that Front Range forested ecosystems are always changing through time, and restoration should focus on creating and sustaining temporal variability in forest structure patterns. Temporal variability can be accomplished by staging restoration treatments through time on the landscape. Such staging of treatments often occurs by default as treatments are implemented through multiple years by various land management agencies and private landowners on the Front Range. Restoration efforts across ownerships are often not coordinated and occur independently of one another. In some ways, such a treatment approach is desirable in that it contains an element of stochasticity not too

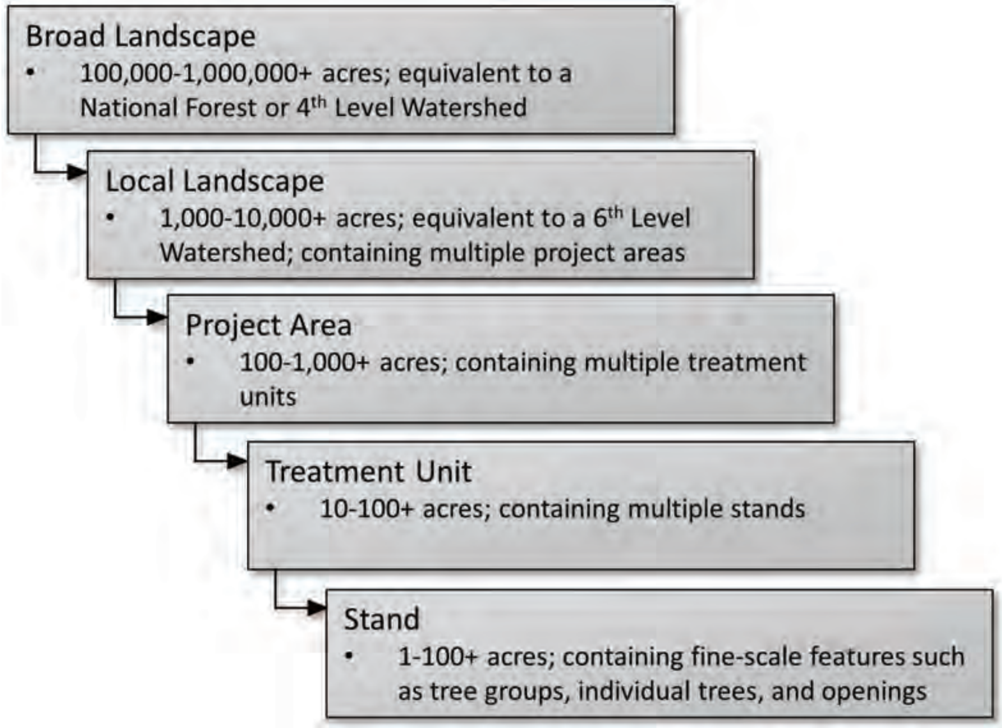

Figure 12—Hierarchy of planning scales.

unlike natural disturbances. There are, however, advantages to being deliberate in planning restoration treatments both spatially (across ownerships) and through time to ensure representation of all desired patch types at the landscape scale.

3.3 Restoration Enhances Desired and Rare Elements of Forest Structure Across Scales

It is useful to think of landscapes and stands in terms of their component parts and to attempt to identify those elements currently missing that are considered important for maintaining desired processes and functions (table 4). At the landscape scale, vegetation patches are an important feature. At this scale, it is difficult to distinguish individual trees or species, but patches of similar forest are visible through aerial or satellite imagery, as are large openings. Patch size, patch composition and structure, patch connectivity, and between-patch variability are all important components of what is often called the landscape mosaic (Lindenmayer et al. 2008; Romme et al. 2003a). Assessing how patch types are distributed both spatially and temporally within the landscape mosaic can help to identify whether restoration is needed, and if so, where restoration activities should occur to best achieve landscape restoration goals (Haugo et al. 2015).

In describing common vegetation patch types for the Front Range, we adopt vegetation characterizations based on traditional models of forest development and vegetation structural stages (Hall et al. 1995; Oliver and Larson 1996; Reynolds et al. 1992; Rollins et al. 2009). Such models typically incorporate canopy cover as well as successional pathways from early, postdisturbance vegetation states to late-successional vegetation states containing large, old trees and often characterized by uneven-aged stand structures. Common vegetation patch types within ponderosa pine and dry mixed-conifer forests on the Front Range include: (1) openings, (2) open-canopy forests, and (3) closed-canopy forests.

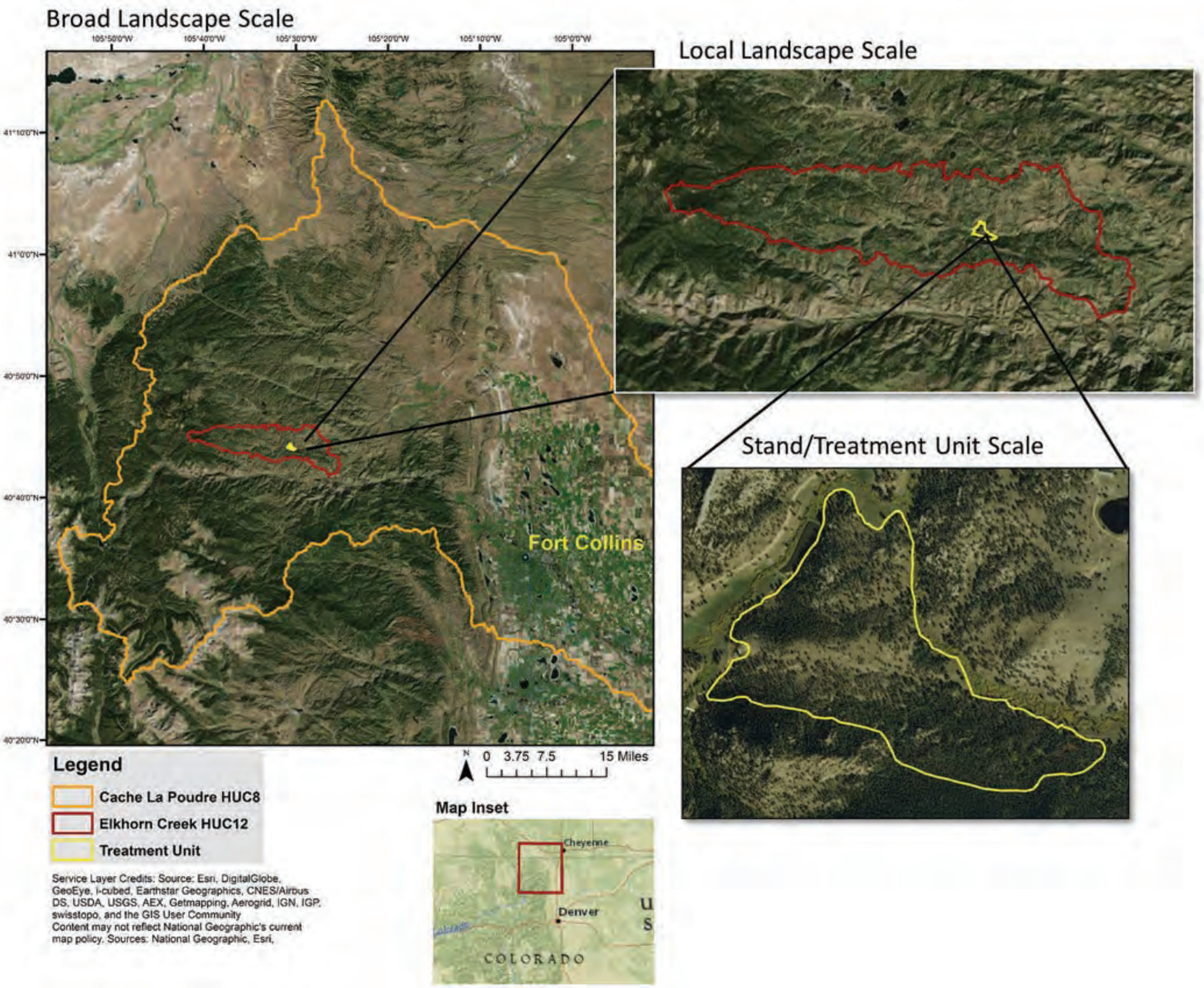

Figure 13—Scales for Front Range forest restoration, beginning with the broad landscape scale (100,000 to 1,000,000+ acres; e.g., HUC-8 watersheds) within which local landscapes occur (1,000 to 100,000+ acres; e.g., HUC-12 watersheds). Stands or treatment units (1 to 100+ acres) occur within local landscapes. Multiple stands or treatment units may make up a project area (not pictured).

Table 4—Hierarchy of scales and associated forest structural elements. For strategic planning and implementation purposes, managers may wish to further subdivide within scales as follows: broad landscape → local landscape → project area → stand or treatment unit.

Scale	Definition	Structural elements
Landscape	Land area characterized by a spatial mosaic of ecosystems, landforms, and vegetation communities irrespective of ownership or artificial boundaries. The landscape scale can be further divided into broad landscapes (on the order of 100,000 to 1,000,000+ acres) and local landscapes (1,000 to 100,000+ acres), but structural elements are similar across these scales.	Landscapes are composed of both forested and nonforested patches of various sizes, shapes, and arrangements controlled by topography, disturbance regimes, and broad climatic patterns.
Stand/treatment unit	An area within which forest management occurs. Individual stands or treatment units may range in size from 1 to 100+ acres and may roll up to form larger project areas 1,000+ acres in size.	Openings, tree groups, and scattered individual trees are all prominent features at the stand or treatment unit scale. Snags and downed wood are important structural elements at this scale as well.

Openings—Openings (both persistent and transient) are an important landscape feature on the Front Range that should be enhanced through restoration efforts. Openings at the landscape scale are defined here as being greater than 1 acre and containing less than 10 percent canopy cover (contrast with openings at the stand scale described later). Trees can occur in openings but are sparse enough that they do not significantly influence ecological processes. Openings are characterized by an abundant understory vegetation layer containing a diverse mixture of grasses, sedges, forbs, and shrubs. Seedlings and saplings may occur within openings as well, especially transient openings which facilitate tree regeneration. Openings as described here are analogous to Vegetation Structural Stage (VSS) 1A (Grass/Forb/Shrub-Open) and 2A (Seedlings/Saplings-Open) in Reynolds et al. (1992), as well as Stage A (Early Seral) in the LANDFIRE Biophysical Setting (BpS) descriptions.

Open-canopy forests—Open-canopy forest patches, defined here as patches with 10- to 40-percent canopy cover, are another important landscape feature in ponderosa pine and dry mixed-conifer forests on the Front Range. Open-canopy forests are often found in dry settings on the Front Range, such as south-facing slopes and ridges, as well as where disturbances such as low-severity fire have maintained open structures through time (fig. 14). Open-canopy forest patches may include both mid- and late-seral developmental stages, equivalent to VSS 3-6A (Young Forest-Open to Old Forest-Open) and LANDFIRE BpS Stage C (Mid-Open) and Stage D (Late-Open).

Figure 14—Ponderosa pine woodland in the Roosevelt National Forest near Red Feather Lakes, Colorado, illustrating an open, low-density stand structure (photo: P. Brown, Rocky Mountain Tree-Ring Research, used with permission).

Closed-canopy forests—Open-canopy forests grade into closed-canopy forests, especially in areas of higher productivity in the absence of disturbance. Closed-canopy forests are defined here as containing more than 40-percent canopy cover. Closed-canopy forest patches may include both mid- and late-seral developmental stages, equivalent to VSS 3-6B (Young Forest-Moderately Closed to Old Forest-Moderately Closed), as well as LANDFIRE BpS Stage B (Mid-Closed) and Stage E (Late-Closed). (VSS models also include a Closed-Canopy classification with canopy cover greater than 70 percent. On the Front Range, however, this stage is less common than Open and Moderately Closed structural stages (Battaglia et al. 2017), so we grouped Moderately Closed and Closed VSSs into a single patch type.) Closed-canopy forests provide opportunity for restoration to open-canopy forests where ecologically appropriate.

Landscape-level vegetation patches are themselves composed of finer-scale features at the stand or treatment unit scale in what Hessburg et al. (2015) describe as patches within patches, or as an interconnected patchwork hierarchy. Common structural elements at this scale include: (1) openings, (2) tree groups, (3) randomly spaced individual trees, (4) snags and downed wood, (5) aspen, and (6) riparian vegetation.

- **Openings—**Openings occur at the stand or treatment unit scale as well, often as the graminoid-forb-shrub interspace between tree groups and individual, scattered trees. Openings at this scale are likely to range from 0.25 acre to several acres and may be either persistent or transient (fig. 15). The range of sizes, dimensions, and spatial distribution is determined by site conditions. Infill of younger trees resulting from historical land use and fire exclusion can make openings at this scale hard to detect (see discussion of "forensic forestry" in section 3.1).
- **Tree groups—**Tree regeneration in frequently burned, uneven-aged forests often occurs in aggregations due to resource availability or "safe sites" created by fuel conditions that protect seedlings from fire, or a combination of both (Larson and Churchill 2012; see section 3.6). This pattern of tree regeneration leads to the formation of tree groups. Trees occurring within close enough proximity to have interlocking crowns define a tree group. The proportion of trees occurring in groups, the number of trees per group, the age-class distribution within and between groups,

Figure 15—Fine-scale (<1 acre) opening within a dry mixed-conifer forest in the Pike National Forest near Woodland Park, Colorado (photo: P. Brown, Rocky Mountain Tree-Ring Research, used with permission).

and the size and spatial distribution of tree groups are all generally dictated by site conditions, such as productivity, as well as by disturbance history.

- **Randomly spaced individual trees—**In addition to tree groups, randomly spaced individual trees are another common feature of ponderosa pine and dry mixed-conifer forests at the treatment unit or stand scale. Higher proportions of individual trees (compared to groups of trees) are expected to occur on low-productivity sites, in dry and rocky settings. The proportion of trees occurring as individuals, as well as the range of tree sizes, ages, and species, is important to consider during restoration planning at the treatment scale.
- **Snags and downed wood—**Legacies from previous mortality events such as snags and downed wood are important for nutrient cycling, microclimates for tree establishment, and wildlife habitat (Franklin 1989; Reynolds et al. 1985, 1992). These structural elements are important for overall stand or treatment unit complexity (Franklin et al. 2007; McElhinny et al. 2005).
- **Aspen—**Small aspen groves or individual aspen stems are a recognizable feature at the stand or treatment unit scale as well and often occur within wetter areas, such as swales or depressions, or adjacent to riparian areas. Aspen provide compositional diversity within stands or treatment units and are a desirable structural element to retain and enhance through restoration activities. Aspen may also serve as a fire break in some cases.
- **Riparian vegetation—**Treatment units that extend into drainages, valley bottoms, or stream and river corridors often contain riparian vegetation such as cottonwoods (*Populus deltoides, P. angustifolia,* and *P.* × *acuminata*) and willows (*Salix* spp.). Like aspen groves, riparian areas provide structural and compositional diversity and are important for a variety of wildlife and plant species, as well as hydrological processes.

Consideration of structural elements across scales is useful for Front Range restoration for several reasons. First, the structural elements themselves provide a framework for restoration, whereby restoration activities can be organized around desirable structural elements. Structural elements in the landscape can be inventoried to better understand their distributions and relative abundance within the landscape. This information can then be used to determine what is common versus rare in the landscape, with restoration activities intended to enhance those rare features that would be expected under an intact disturbance regime (Haugo et al. 2015). A similar process can be applied at the stand scale. In this way, the structural elements become anchors around which restoration can be conceptualized from planning phases through implementation. Restoration guidelines from other regions have taken this approach. For ponderosa pine and dry mixed-conifer forests in Arizona and New Mexico, for example, Reynolds et al. (2013) organize restoration recommendations by key elements of forest structure such as tree groups, scattered individual trees, graminoid-forb-shrub interspace, and biological legacies including snags, logs, and downed wood. They also point out the importance of variability in these elements both spatially and temporally.

Consideration of structural elements across scales also improves our understanding of how variability at one scale is related to variability at other scales. A central goal of restoration is to enhance variability across scales to form a diverse landscape mosaic that is resilient to future disturbances and climate change. Fine-scale variation in tree density, tree spatial pattern, and openings is likely to increase the prevalence of mixed-severity fires (consistent with historical dynamics) whereby areas of higher tree density may burn with fine-scale, localized high-severity fire effects, but these areas are interspersed with openings that facilitate low-severity fire (Churchill et al. 2013b). Conversely, continuous high-density, homogeneous structures at fine scales may create continuous high-density forests at larger scales, which, in turn, are more susceptible to extensive tree mortality.

Organizing landscape- and treatment-level prescriptions around desired structural elements also encourages emphasis on what to retain as opposed to what to extract. This is consistent with a retention-based approach to management, whereby the focus of management is to improve landscape and stand condition by specifying what to retain, how much to retain, and the spatial pattern of retention of desired elements (Franklin and Johnson 2012; Franklin et al. 2007). Restoration should retain and enhance the full complement of forest structures appropriate to the landscape to provide options for adaptation and resilience (Stine et al. 2014).

3.4 Restoration Complements Natural Variation in Forest Structure by Environmental Gradients

The spatial pattern of forest structural elements at landscape and stand scales in mountainous terrain is heavily influenced by environmental gradients that coincide with topographic variation (Hadley 1994; Lydersen and North 2012; Peet 1981; Urban et al. 2000). Key gradients we consider important for restoration work on the Front Range include latitude, elevation, aspect, slope position and steepness, and soils. Moisture gradients typically underlie these physical gradients due to interactions among precipitation, temperature, and solar radiation (Allen et al. 1991; Kane et al. 2015; Parker 1982). These gradients also mediate disturbance and forest developmental processes in important ways, as described in more detail next.

3.4.1 Latitude

Environmental variables such as solar radiation and precipitation change broadly with latitude from south to north along the Front Range (fig. 16), discussed in more detail in panel 3. The Palmer Divide between Denver and Colorado Springs is an important geological feature that serves as somewhat of a dividing line between the southern Front Range and the northern Front Range through its influence on weather patterns, soils, and vegetation dynamics (von Ahlefeldt 1992).

3.4.2 Elevation

At a given latitude, environmental conditions vary dramatically with changes in elevation on the Front Range. Soil moisture increases with elevation due both to greater mean annual precipitation at higher elevations and to lower temperatures and evaporation at higher elevations (Lukas et al. 2014). Precipitation can increase by as much as two-fold along an elevational gradient from the plains to the alpine tundra, where winter precipitation dominates and snowpack can remain for most of the year (Birkeland et al. 2003; Veblen and Lorenz 1991). Similarly, mean annual temperature can decrease by as much

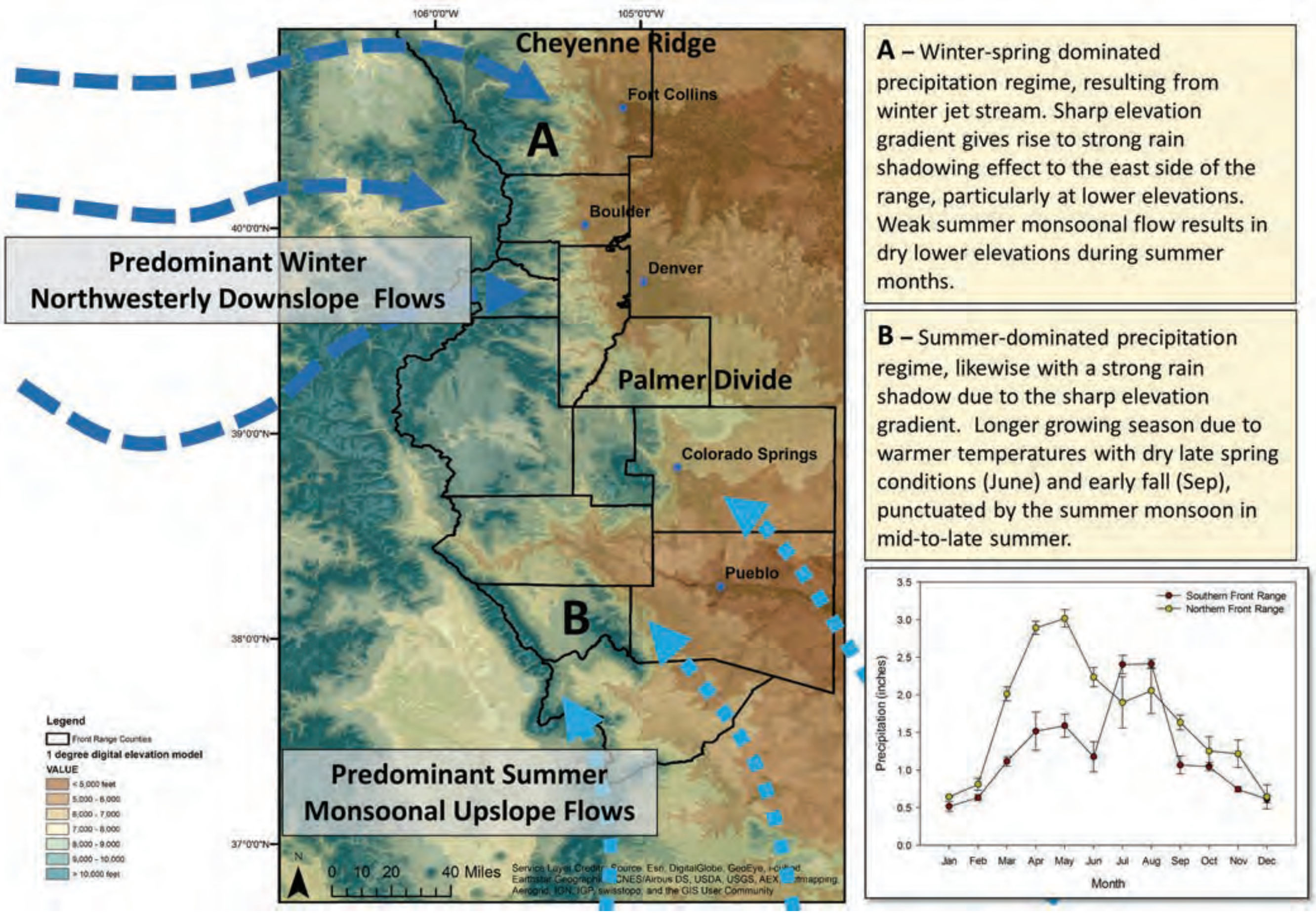

Figure 16—Precipitation patterns across the Front Range. Line chart inset represents precipitation data averaged for three weather stations on the northern Front Range (Red Feather Lakes, 1941–1990; Buckhorn Mountain, 1988–2011; and Gross Reservoir, 1978–2012) and three stations on the southern Front Range (Cheesman Lake, 1902–2012; Westcliffe, 1895–2011; and Sheep Mountain, 1988–2011).

as 25 °F from the plains to the tundra, leading to shorter growing seasons at higher elevations. Longer duration of snowpack is important for delivering moisture to high-elevation plant communities later into the spring compared to lower elevations. Tree density, productivity, and fuel accumulation typically increase with elevation in the montane zone as well due to higher moisture availability (Peet 1981).

3.4.3 Aspect

At a given elevation, soil moisture is greater on north-facing slopes compared to south-facing slopes due to lower solar radiation, lower temperatures, and lower evaporation (fig. 17). Where snowpack occurs during winter (typically above ~9,000 feet), it usually persists longer into the spring on north-facing slopes compared to south-facing slopes. Higher moisture availability on north-facing slopes allows for a wider range of forest structure patterns, from openings to closed-canopy forest patches (fig. 18). Fire behavior may also be more variable on north-facing slopes than on south-facing slopes, due to higher variability in fuel loads and fuel moisture conditions.

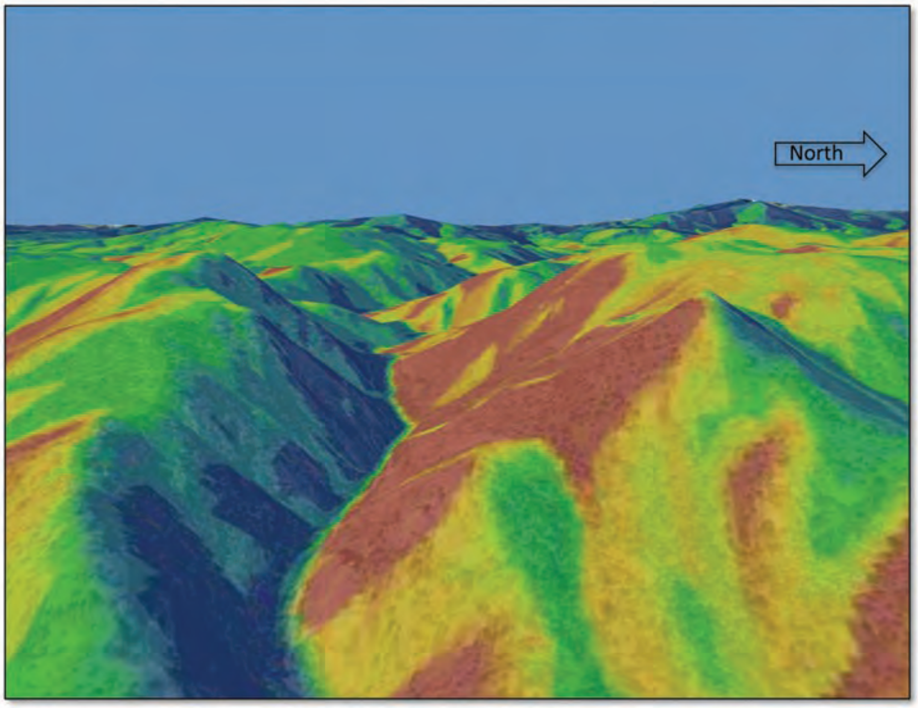

Figure 17—Variation in moisture with topography. Moisture increases over broad scales with increasing elevation, as well as over smaller scales with changes in aspect and slope position. Ridges and south-facing slopes are typically dry due to their exposure and solar radiation (shaded red), whereas north-facing slopes and slope bottoms are moist due to shading, hydrological processes, and soil developmental processes (shaded blue). Topographic moisture patterns based on 30-year PRISM precipitation trends, solar insolation, and topographic influences on water flow and accumulation; developed by J. Norman and J. Feinstein, Natural Resources Conservation Service.

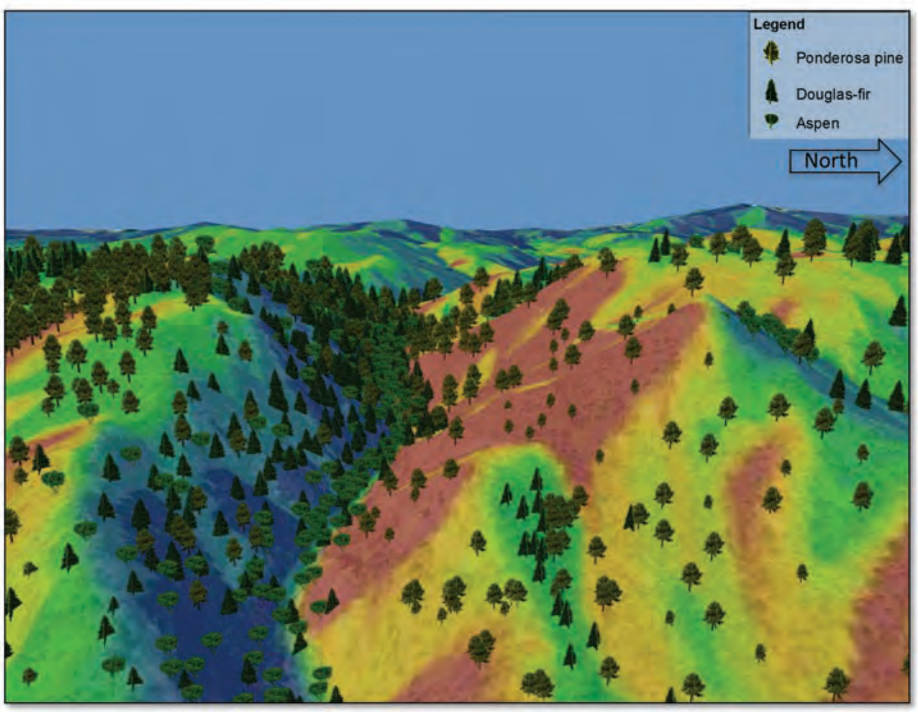

Figure 18—Variation in forest structure reflecting topographic influences and underlying moisture gradients. South-facing slopes are characterized by open, ponderosa pine woodlands with trees occurring both in groups and as scattered individuals. Forest density increases in areas with higher moisture, such as north-facing slopes. The proportion of Douglas-fir typically increases as well with increasing moisture. Aspen is also an important component of forest structure, typically occupying areas with higher moisture availability.

3.4.4 Slope

Moisture increases with elevation over broad scales, but at smaller scales, such as individual hillslopes, moisture typically decreases from slope bottoms to ridge tops. Increased exposure also accompanies the elevational increase at this scale such that ridges often experience harsh, windy conditions. Tree density typically decreases from slope bottoms to mid-slopes to ridges (Dickinson and SHSFRR 2014; Lydersen and North 2012; North et al. 2009). Moisture varies with slope steepness as well, with shallow slopes (<20 percent) typically having higher moisture availability compared to steep slopes (>40 percent), due to deeper soils on gentle slopes. Steep slopes are also prone to soil loss, especially after disturbance events such as fire (Morris and Moses 1987; Peet 1981).

3.4.5 Soils and Other Environmental Gradients

The subsurface and parent material for soil formation along the Front Range is primarily granite, gneiss, and schist (Lovering and Goddard 1950), and soils tend to be immature, rocky, shallow, coarse-textured, and slightly acidic (Johnson and Cline 1965). Dominant soil orders include Mollisols, Alfisols, Inceptisols, and Entisols (Natural Resources Conservation Service [NRCS] 2017). Mollisols are characteristic of grassland ecosystems and on the Front Range are often associated with mountain grasslands and persistent openings. Alfisols are associated with forested ecosystems, and Inceptisols and Entisols are typically found in steep, rocky terrain (NRCS 2017). On the Front Range, soils vary broadly with latitude based on geological influences and the presence of the Pikes Peak batholith in the southern Front Range (panel 3). Topographic aspect also influences soil formation processes; south-facing slopes often lack an O-horizon (organic matter or humus), whereas north-facing slopes may have relatively thin O-horizons (Birkeland et al. 2003).

For restoration work, it is important to consider how environmental gradients shape forest structure and composition dynamically over space and time, and it is important to work with these natural gradients in locating and designing treatments. We recommend that planners characterize natural gradients both within a landscape and within treatment units and allow these natural gradients to dictate how patch types and structural elements described in section 3.3 are distributed during the treatment design phases of restoration (Abella et al. 2013; Dickinson and SHSFRR 2014; North et al. 2009).

Use of site water balance metrics such as the topographic relative moisture index (TRMI) or topographic wetness index (TWI) can be helpful in identifying underlying moisture gradients that influence forest structure and composition (Parker 1982). These indices typically integrate the effects of topographic position, slope aspect, steepness, and insolation on moisture availability and can be applied at a range of scales. Dry areas within a landscape identified through the TWI may provide opportunities for creating openings or low-density forest structures (fig. 19). Similarly, wet areas identified through the TWI may be appropriate for retaining high-density forest structures. Tools such as the TWI can also be applied at a range of scales. At the stand or treatment scale, fine-scale variation in moisture gradients can help in determining where to create smaller-scale openings and where to retain tree groups as well as denser pockets of trees. Partitioning the landscape by land facets or topographic categories is another useful, though less direct, way to capture the environmental variation that accompanies topography (Underwood et al. 2010).

Panel 3—Variation From South to North Along the Front Range

- **Climate** varies with latitude on the Front Range, with solar radiation and temperature decreasing from south to north (Barry 1992). Precipitation also varies with latitude, peaking in July–August in the southern Front Range and April–May in the northern Front Range (fig. 16) (Veblen and Donnegan 2005). Proportionately more precipitation occurs in the summer months in the southern Front Range than in the northern Front Range due to stronger monsoonal weather patterns in the southern Front Range (Veblen et al. 2000).

- The **elevation of tree line** (i.e., the forest to alpine tundra ecotone) decreases from south to north along the Front Range. Consequently, the elevational zone of montane ponderosa pine and dry mixed-conifer forests extends to higher elevations in the southern Front Range compared to the northern Front Range (Brown and Shepperd 2001; see also figure 1 in Kaufmann et al. 2006). This variation in tree line suggests that we should not choose a hard elevational cutoff across the entire Front Range where restoration is (or is not) an appropriate management goal. Restoration activities may be warranted at higher elevations in the southern Front Range (e.g., above 9,000 feet in elevation) than in the northern Front Range.

- The historical **zone of low-severity, frequent fire** extends to higher elevations in the southern Front Range compared to the northern Front Range, coincident with latitudinal variation in climate and vegetation distributions. Brown and Shepperd (2001) also document shorter fire return intervals in the southern Front Range compared to the northern Front Range, as well as increased incidence of early growing season fires in the southern Front Range. Thus, the window for fire management may be longer in the southern Front Range, but managers should also plan for longer wildfire seasons in the southern Front Range compared to the northern Front Range.

- Important differences in **species composition** exist between the southern and northern Front Range. White fir and Gambel oak occur in the southern part of the Front Range but not in the northern Front Range (Peet 1978). Both white fir and Gambel oak are capable of prolific regeneration in the understory. White fir can form dense ladder fuels. Gambel oak is capable of regenerating vegetatively from root stocks and resprouts prolifically following top-kill from disturbance such as fire. As a result, Gambel oak can present a management challenge in ponderosa pine stands by forming a uniform layer of regeneration that may competitively exclude ponderosa pine seedlings and desired understory herbaceous vegetation. The Pike National Forest also contains plantations that were established in the 1920s and 1930s following original forest clearing that occurred with settlement. These areas may require management beyond what is presented in this document.

- The presence of **granitic soils** associated with the Pikes Peak batholith in the southern Front Range represents an important distinction from the northern Front Range. Granitic soils are characterized by low water-holding capacity, potentially making forests in the southern Front Range more drought-prone. Therefore, lower density forest structures and retention of drought-tolerant species such as ponderosa pine are particularly appropriate management goals in the southern Front Range.

3.5 Natural Patterns of Tree Mortality Inform Restoration Practices

Topography and moisture gradients provide the biophysical template against which disturbances such as fire further shape forest structure and composition. Peet (1981) describes Front Range forests as "disturbance phenomena" and points out the need for viewing Front Range forest ecology in the context of disturbance and the patterns of forest recovery following disturbance. Natural disturbances operate over different return intervals, from short to long, and over different spatial scales, from individual trees to entire landscapes, with a wide range of resultant effects on forest composition and structure

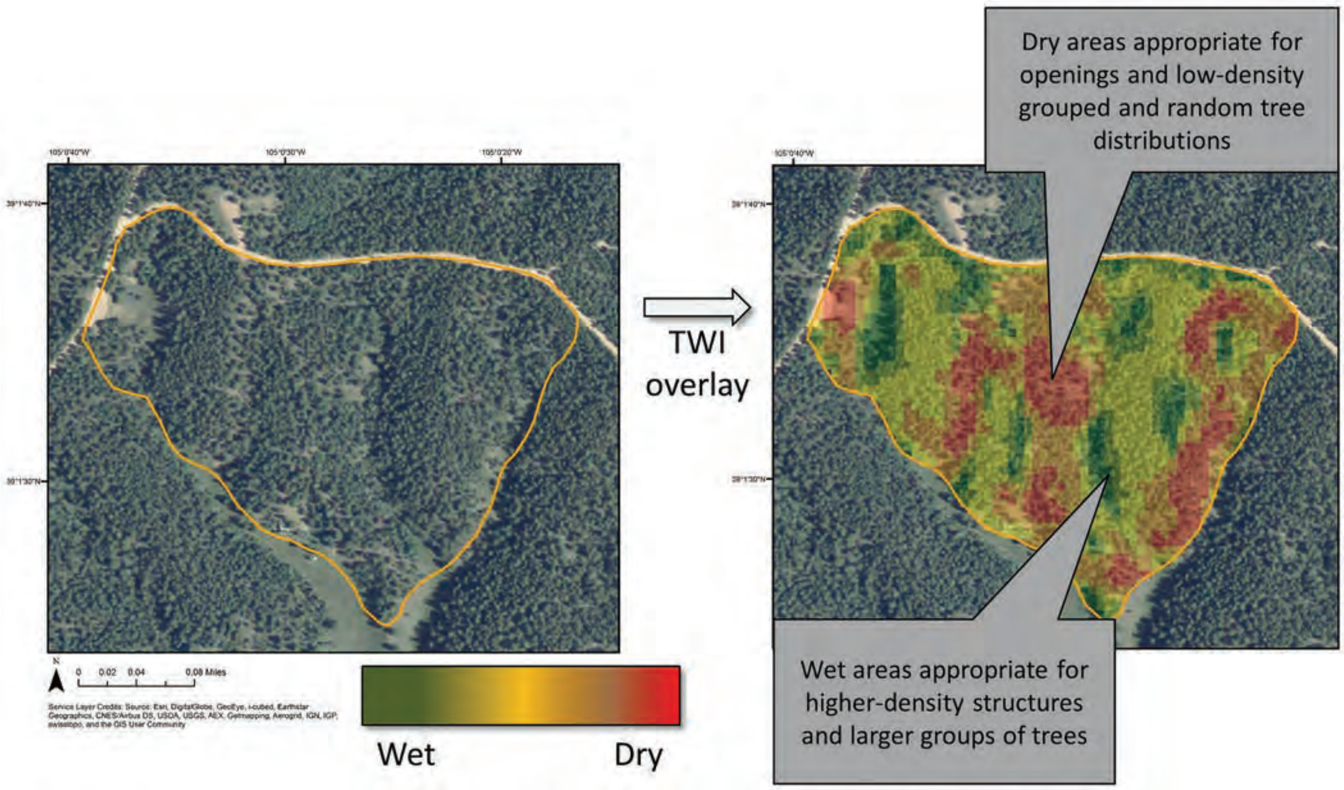

Figure 19—Fine-scale variation in moisture availability at the stand scale based on a topographic wetness index (TWI). Within-stand gradients in moisture may be used to locate various structural features. Openings are appropriate in dry (red) areas, and higher-density tree groups are appropriate in wet (green) areas. Intermediate areas (yellow and orange) are appropriate for low-density tree groups and randomly spaced individual trees.

(Franklin et al. 2007; Romme et al. 1998). Fire, insects and disease, lightning, and windthrow are the primary natural disturbance agents affecting Front Range ponderosa pine and dry mixed-conifer forests, with fire being the most prominent and historically important (Ehle and Baker 2003; Peet 1981; Veblen and Donnegan 2005).

Fire frequency, extent, seasonality, and severity (i.e., the fire regime) were historically influenced by complex interactions among topography, fuels, and climate on the Front Range (Baker 2003; Brown et al. 1999; Kaufmann et al. 2006; Romme et al. 2003b; Sherriff and Veblen 2008; Veblen and Donnegan 2005). The Front Range fire regime is considered mixed severity (panel 4). Historically, lower montane ponderosa pine and dry mixed-conifer forests most often experienced fires that were primarily low-severity, frequent surface fires, with a return interval anywhere from 1 to approximately 35 years, depending on the scale of measurement (Brown et al. 1999, 2015; Goldblum and Veblen 1992; Kaufmann et al. 2006; Platt et al. 2006; Romme 2005; Sherriff and Veblen 2007; Veblen et al. 2000; see panel 4 for a discussion of the importance of scale in evaluating fire return intervals). These fires would be carried by surface fuels such as pine needles and herbaceous vegetation and would result in very little canopy mortality. They would occur frequently enough to prevent heavy fuel accumulation. Nonetheless, it was not uncommon for patches of trees to completely burn in these settings, resulting in high-severity fire effects, depending on fine-scale topography and weather conditions (Baker 2003, 2015; Romme 2005; Veblen et al. 2000).

Panel 4—Definitions of Fire Severity and Fire Return Interval

The term "fire severity" refers to the effects of fire (wildland or prescribed) on vegetation and soils (Agee 1996; Keeley 2009). Fire severity is often categorized as low, moderate, high, or stand-replacing based on the percentage of canopy mortality caused by fire. Common literature definitions of fire severity categories are as follows (Agee 1996; Hessburg et al. 2007b; Sherriff et al. 2014):

- **Low-severity fire:** less than 30-percent mortality of total canopy cover or less than 20-percent mortality of overstory trees.
- **Moderate-severity fire:** between 30- and 70-percent mortality of total canopy cover or between 20- and 80-percent mortality of overstory trees.
- **High-severity fire:** greater than 70-percent mortality of total canopy cover or greater than 80-percent mortality of overstory trees.
- **Stand-replacing fire:** 100-percent mortality (or nearly 100-percent mortality) of total canopy cover.

Many forest types of the western United States exhibit all four severity types in what is referred to as a "mixed-severity fire regime" (Hessburg et al. 2007b; Perry et al. 2011). Front Range ponderosa pine and dry mixed-conifer forests are likewise characterized by a mixed-severity fire regime. The proportion of low-severity fire is highest in lower-elevation settings and lowest in upper-elevation settings, where moderate- and high-severity fire proportionally increases.

Fire severity can be highly variable across a landscape and within a landscape patch based on topography, weather, and fuels (Kaufmann et al. 2006). Because of this, the concept of fire severity is very coarse when applied across a large area and has an element of subjectivity when determining cutoffs between categories. The interpretation of fire severity can be confounded by scale as well. For example, a 100-acre fire that contains 10 acres of high-severity fire is much different in ecological effect from a 100,000-acre fire that contains 10,000 acres of high-severity fire (Stephens et al. 2014), yet both fires would be considered mixed-severity. In this document, we apply the concept of fire severity as a heuristic to describe what is known about general tendencies of fire frequency and effects on forest structure across large areas over long time periods. However, field-based assessments to approximate fire history and historical forest structure are recommended to develop local, site-specific information to guide restoration assessment and planning.

Fire return interval is another important concept, used to refer to the time between fires in a given area. In this document, we describe the lower montane as being characterized by a frequent fire return interval, with fire occurring every 1 to approximately 35 years (Brown et al. 1999; Platt et al. 2006; Veblen et al. 2000). This variability in fire return intervals is influenced in part by the spatial scale over which fire scars are assessed. Both Brown et al. (1999) and Huckaby et al. (2001) describe an inverse relationship between fire return interval and scale, with larger areas having shorter fire return intervals. This inverse relationship emerges because the probability of having a fire within a given 0.5-acre area, for example, is much lower than the probability of having a fire somewhere within a 5,000-acre area. Thus, when averaged over both areas, the mean fire return interval will be lower for the larger area compared to the smaller area. In lower montane settings of the Front Range, the 1- to 35-year return interval applies primarily to a scale less than 250 acres, approximating the size of a stand or project area, as defined in section 3.2 of this document. It is important to recognize, however, that many areas in the lower montane of the Front Range may go longer than 35 years between fires, whereas other areas may have much more frequent fire.

Both fire severity and return intervals typically increased historically with increasing elevation (Brown and Shepperd 2001; Schoennagel et al. 2011; Veblen et al. 2000). Prolonged or severe drought conditions were generally required for large-scale fire to spread in upper elevation forests (Sherriff and Veblen 2008). Historical fire is believed to have occurred every 35 to 100+ years in upper montane forests, and the proportional area of moderate- and high-severity fire was also generally greater at higher elevations (Kaufmann et al. 2006; Schoennagel et al. 2011; Sherriff and Veblen 2007; Veblen et al. 2000). For example, within the upper montane zone from 7,900 to 9,200 feet, Schoennagel et al. (2011) found that 62 percent of their sampled area historically burned with moderate severity and 38 percent burned with high severity. Sherriff and Veblen (2007) also documented increased incidence of mixed-severity fire with increasing elevation in the northern Front Range. They estimated that as much as 80 percent of their study area (150,361 acres within an elevational range of 5,900 to 9,800 feet in the Arapaho-Roosevelt National Forest) historically burned with a mixed-severity fire regime, whereas 20 percent burned under a low-severity, frequent fire regime. Low-severity, frequent fire was restricted primarily to lower-elevation ponderosa pine forests. In a more recent study in the north-central Front Range, Sherriff et al. (2014) found that about 28 percent of Front Range forests burned with predominantly low-severity fire, whereas 72 percent of the study area was characterized by mixed-severity fire (fig. 20).

Variation in fire severity and return intervals also accompanies variation in slope and aspect. Gentle slopes were historically more likely to support a low-severity fire regime, whereas areas of more dissected and complex topography were more likely to experience moderate- or high-severity fire (Hadley 1994; Jain et al. 2012; Kaufmann et al. 2006; Noss et al. 2006; Romme 2005; Sherriff et al. 2014). Flame lengths, fire spread rate, and severity may be higher on steep slopes, particularly if burning uphill, due to preheating of fuels upslope of the flaming front (Arno 2000; Pyne et al. 1996). South-facing slopes may also be more likely to support frequent, low-severity fire compared to north-facing slopes, due to the more xeric conditions associated with southern aspects and lower fuel loads and stand densities (Hadley 1994). Proximity to grasslands is another factor shown to be important in influencing fire frequency in Front Range ponderosa pine, with stands adjacent to grasslands exhibiting higher fire frequency than stands farther from grasslands (Gartner et al. 2012).

Although general patterns in fire behavior exist with elevation, slope, and aspect, it is important to recognize that fire is a very dynamic process and fire return intervals, behavior, and extent can be highly variable from place to place and from fire event to fire event on the Front Range (Brown et al. 1999; Kaufmann et al. 2006; Romme et al. 2002a). For example, south-facing slopes may have historically burned with high severity in some cases due to the more extreme environmental conditions typically found on south-facing exposures, especially during wind-driven fire events. In other instances, lack of fuel on south-facing slopes may have inhibited fire intensity and spread (Huckaby et al. 2001). Likewise, dense forest conditions on north-facing slopes may have encouraged high-severity fire under extreme weather conditions (Baker et al. 2007), or fire may not have spread at all in these situations if fuel moisture conditions were high (Noss et al. 2006; Taylor and Skinner 2003). There is also emerging evidence for low-severity fire regimes on north-facing slopes, based on the presence of old, fire-scarred ponderosa pine trees and historically open forest conditions from stand reconstruction data (Battaglia et al. 2017; Braun et al. 2015).

In addition to fire, insects and pathogens are important in shaping forest structure and composition on the Front Range (Alexander 1986; Ehle and Baker 2003; Veblen and Donnegan 2005). Mountain pine beetle, Douglas-fir tussock moth, Douglas-fir bark beetle (*Dendroctonus pseudotsugae*), western spruce budworm, and dwarf mistletoe, among others, are all believed to have been historically important (Alexander 1986;

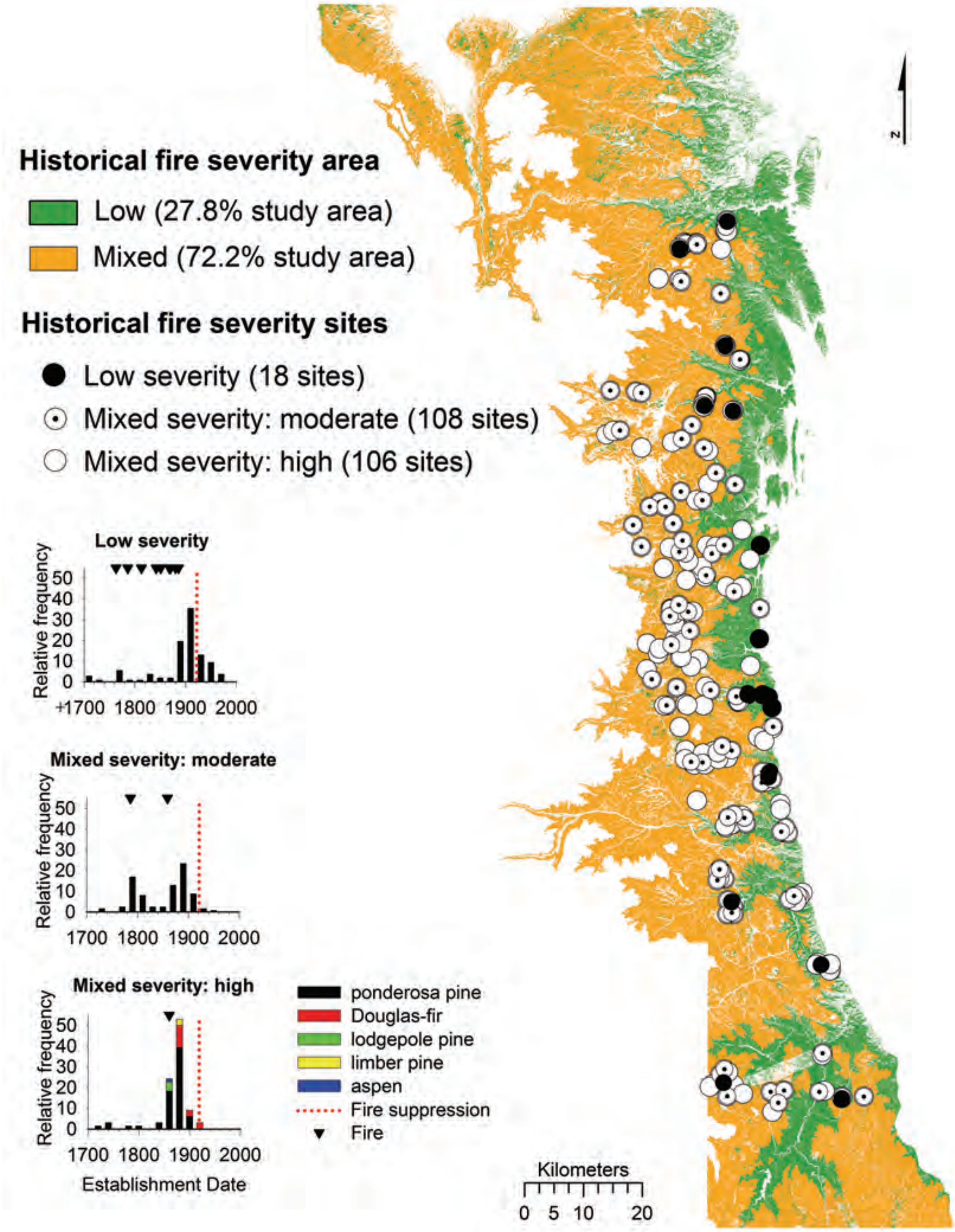

Figure 20—Proportion of the Front Range characterized by historical low-severity and mixed-severity fire (figure: Sheriff et al. 2014, used with permission).

McCambridge et al. 1982; see Veblen and Donnegan 2005 for a more comprehensive review). Insect outbreaks are within the HRV for the Front Range and are often correlated with climate. For example, the mountain pine beetle is restricted by cold winter temperatures, and outbreaks may occur when winter temperatures are not cold enough to limit the life cycle of this species (Veblen and Donnegan 2005). In general, insects and pathogens tend to be species-specific in their effects on forest stands, in contrast to fire, and therefore typically affect some but not all trees in a stand. Furthermore, they may affect trees of different ages and sizes disproportionately in a given area, depending on their population sizes. Mountain pine beetles, for example, attack weak, stressed, and relatively smaller-diameter pines when their numbers are at low, endemic levels, but kill older and larger trees under epidemic outbreak conditions when populations are large (Negrón and Popp 2004). Unlike fire, insects and pathogens do not directly disturb the forest floor, which results in a different regeneration environment than is present in burned areas.

Lightning and windthrow are also important mortality agents in Front Range ponderosa pine and dry mixed-conifer forests, but are typically smaller in magnitude and scale compared to fire, insects, and pathogens. Lightning tends to kill individual trees or small groups of trees. Windthrow events may be somewhat broader in scale than lightning and may be locally important, but are generally not a primary disturbance agent in montane forests (Alexander 1986). Both ponderosa pine and Douglas-fir are wind-firm and less susceptible to windthrow due to deep rooting, compared to species in the subalpine zone (Oliver and Ryker 1990; Veblen and Donnegan 2005).

Understanding natural disturbance regimes is important for restoration because it provides us with a sense of how tree mortality naturally occurs in Front Range ponderosa pine and dry mixed-conifer forests, especially the scale and interval of tree mortality. Tree mortality is the process most closely mimicked by forest restoration treatments, as treatments often involve tree removals. An understanding of natural patterns of tree mortality can inform restoration treatment design, as restoration often seeks to mimic or emulate the way in which natural disturbance shapes landscape and stand structures (Drever et al. 2006; Franklin et al. 2007; Perera and Buse 2004; Seymour and Hunter 1999).

Patch mortality (i.e., mortality of multiple trees) is a particularly important phenomenon in ponderosa pine and dry mixed-conifer forests, with patch size of mortality being highly variable depending on the nature of the disturbance agent. Mixed-severity fire, for example, creates mortality patches of varying size and dimension depending on the degree and extent of fire severity. Where stand-replacing fire occurs, mortality may be widespread with all trees in a patch killed, whereas moderate- and high-severity areas may contain small patches of mortality intermixed with unaffected trees, and low-severity areas contain little or no mature tree mortality. In the Cheesman Reservoir landscape of the Pike National Forest, Kaufmann et al. (2000) used present-day openings as an indicator of historical mortality patch size created by a stand-replacing fire in 1851 and found openings ranging from 2.5 to nearly 50 acres. Openings occupied 10 to 25 percent of the total Cheesman landscape area (Kaufmann et al. 2003). The remainder of the landscape was mostly occupied by low-density forest structures (10- to 40-percent canopy cover). Using General Land Office survey information, Williams and Baker (2012a) found that the geometric mean of historical high-severity patch sizes across the Front Range was about 420 acres. Sherriff et al. (2014) estimated stand-replacing patch sizes of approximately 125 acres. This wide range of variation in patch sizes may reflect variation that occurred across the landscape historically, but it may also result from differences in methods and interpretations of different researchers (see Fulé et al. [2014] and Williams and Baker [2014]).

Patches of tree mortality are also created during insect population outbreaks; these are more difficult to identify in past records but historically may have been smaller in scale than that observed on the landscape in recent decades because current forest conditions represent increased homogeneity of tree size and forest extent and hence larger continuous areas of susceptibility (Hadley and Veblen 1993; Swetnam and Lynch 1993; Turner et al. 2013). Not all trees within an affected patch die because of insect attack, as trees tend to vary in their susceptibility to insects based on tree size or age (Negrón and Popp 2004). Patch size of insect-caused mortality observed in recent decades is highly variable, with affected groups ranging from two to three trees to hundreds of trees per acre (fig. 21). For example, McCambridge et al. (1982) described numerous groups of 25 to 50 beetle-killed ponderosa pine trees scattered throughout the Front Range during the mountain pine beetle outbreak of the 1960s and 1970s. Within a 22-acre study area on the Pike National Forest, Boyden et al. (2005) found a mean mortality patch size of about 0.3 acre (65-foot radius), with 16 dead trees per patch on average. West et al. (2014) and Briggs et al. (2015) recorded between 1 and more than 100 beetle-killed pines per acre in Front Range forest surveys conducted from 2009 through 2011. Patch size may enlarge as a result of subsequent attacks following initial attacks, and neighboring patches may merge to form larger affected groups. McCambridge et al. (1982), for example, documented a 163-acre

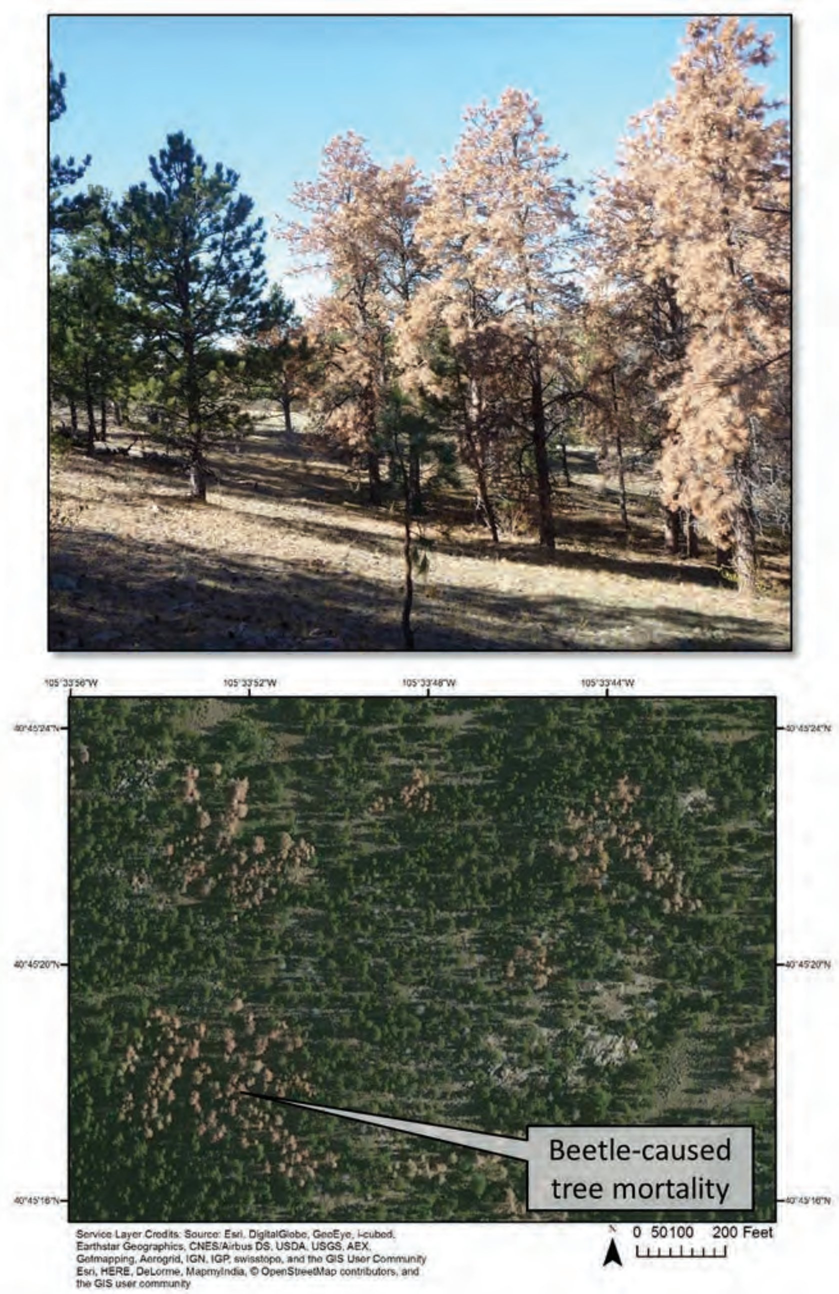

Figure 21—(a) Ponderosa pine tree mortality as a result of mountain pine beetle in Larimer County, Colorado (photo by J. Briggs, U.S. Geological Survey); (b) aerial image of 1- to 3-acre patches of beetle-caused mortality in Larimer County. Mountain pine beetle often kills trees in groups, thereby creating openings for understory vegetation development and tree regeneration.

contiguous area of heavy ponderosa pine mortality in 1978 in Lory State Park near Fort Collins, though many trees survived within the patch.

Given the variation in historical and recent patterns of tree mortality from fire, insect outbreaks, and other ecological disturbance processes, what guidelines can forest managers adopt when planning treatments that simulate aspects of those characteristic disturbance types? This broad range of variability in how disturbance manifests itself both spatially and temporally on the landscape implies (1) that a broad range of structures should exist across the landscape and (2) any given area could have historically been characterized by a range of structures depending on time since disturbance and forest developmental stage. For example, a given north-facing slope could be characterized by closed-canopy forest if fire has not occurred for a long time. Alternatively, the same north-facing slope could contain a large opening or plant communities that are in an early-seral developmental stage representing recovery from recent fire. Likewise, areas that primarily experienced surface fire historically were probably characterized by open, uneven-aged stand conditions with a diverse mixture of tree groups, individual trees, and fine-scale (<1 acre) openings (Larson and Churchill 2012). For a given landscape or treatment unit, planners should seek to understand the disturbance patterns that occurred historically and the range of forest structures most likely to result from those disturbances (table 5).

The range of variability in forest structure for a given site also provides managers with a range of treatment options. The choice of treatment type, however, should be informed

Table 5—Characteristics of mixed-severity fire regimes (containing both low-severity and moderate- to high-severity fire patches) for Front Range ponderosa pine and dry mixed-conifer forests, adapted from Kaufmann et al. (2006), Veblen and Donnegan (2005), and Veblen et al. (2012). Figure 20 depicts the spatial distribution of fire regimes for the Front Range based on Sherriff et al. (2014).

	Low-severity fire	Moderate- and high-severity fIre
Historical occurrence	Lower montane ponderosa pine and dry mixed-conifer forests, as well as areas of gentle topography at higher elevations.	Upper montane dry to wet mixed-conifer forests and areas of complex, dissected, and steep topography at lower elevations.
Fire behavior and effects	Fuels are the dominant driver; shorter fire return intervals compared to moderate- and high-severity fire; fire consumes mainly surface fuels resulting in more homogeneous effects at the landscape scale but high variation at fine scales; little to no canopy mortality but may kill some small trees and patches of regeneration.	Weather is a more prominent driver; fuels are present but "available" only during dry periods; generally longer fire return intervals compared to low-severity fire; characterized by the presence of passive or active crown fire, or both, resulting in more heterogeneous fire effects at the landscape scale and higher canopy mortality.
Forest structures	Uneven-aged, low-density, open forest structure containing tree groups, scattered individual trees, and small openings; tree regeneration often occurring in small aggregations within openings.	Higher tendency toward even-aged or two-aged patches representing various stages of recovery following fire; large, high-density tree patches can be present, as can large openings; high juxtaposition of early- and late-seral vegetation; high amount of edge between seral stages.
Effects of fire exclusion	Reduced mortality of seedlings and saplings, leading to higher rates of tree regeneration and expansion into openings; loss of fine-scale spatial heterogeneity; degradation of understory vegetation communities, buildup of fuels, and increased potential for uncharacteristic high-severity wildfires.	Loss of diverse range of patch types/seral stages, especially early-seral patches due to tree infill; decrease in characteristic, patchy high-severity fire and increase in potential for uncharacteristically large patches of high-severity stand-replacing fire; degradation of understory vegetation communities.

by the landscape context; in other words, planners could ask: What structural elements might be missing that would be desirable to restore? More specifically, through field-based assessments, planners can identify both common and rare structural elements on the current landscape and manage for those rare elements. For example, if openings are absent in the current landscape, then a variably sized patch cut may be an appropriate treatment option to mimic fine-scale patches of high-severity fire. If, however, low-density, spatially heterogeneous forest patches are rare in the current landscape, then an uneven-aged group selection and retention approach that enhances spatial variability throughout the treatment area may be most appropriate.

3.6 Restoration Promotes Variable Tree Regeneration and Diverse Forest Developmental Trajectories

Tree mortality often creates opportunities for tree regeneration, with the patch size of mortality often dictating the patch size of regeneration and, hence, the development of variably sized tree groups as a structural feature. Several studies have highlighted the importance of restoring the "groupy-clumpy" stand structure (also known as ICO—individuals, clumps, and openings) characteristic of frequent-fire forests (Brown et al. 2015; Churchill et al. 2013a; Franklin et al. 2013; Larson and Churchill 2012; Reynolds et al. 2013). Larson and Churchill (2012) describe a mechanism for tree group formation based on complex interactions among fire, tree mortality, and regeneration. They highlight the important role of "safe sites," which are formed in frequent-fire forests when individual trees or small groups of trees die because of mortality agents such as lightning, windthrow, or isolated insect attack. These trees eventually fall and create locally heavy fuels, which can burn more intensely than the surrounding matrix when fire occurs. This locally intense fire behavior creates an opening or gap in the understory vegetation layer and exposes bare mineral soil, providing a suitable seedbed for regeneration. Assuming the presence of seed trees and favorable climatic conditions, highly aggregated regeneration may develop within the safe site (fig. 22).

Figure 22—Aggregated ponderosa pine regeneration on the Roosevelt National Forest near Red Feather Lakes, Colorado (photo: R. Addington, The Nature Conservancy, used with permission).

In ponderosa pine forests, canopy openings created by individual or group tree mortality let sunlight reach the forest floor and reduce overstory competitive effects, favoring shade- and competition-intolerant ponderosa pine seedlings (Minore 1979). The canopy opening also minimizes the accumulation of fine fuels (needle-cast) near the newly established seedlings, and thus, seedlings may be somewhat protected from subsequent fires. Regeneration groups may be highly variable in size, based on the size of the canopy opening. Individual groups will also lose members through competitive exclusion or noncompetitive mortality through time. As the group ages and dominant trees emerge, the original grouped pattern may become less evident (Boyden et al. 2005; Mast and Veblen 1999). As a result, mature trees in older forests often begin to take on a more random arrangement. Regeneration may continue to occur in an aggregated pattern within safe sites, perpetuating the process and mechanism just described and leading to a rich mosaic of regeneration patches interspersed with groups, scattered individual trees, and openings across the landscape.

For Douglas-fir, the safe-site mechanism is likely to be less important, as Douglas-fir has less stringent regeneration requirements and is not as sensitive to shade and competition as ponderosa pine. Douglas-fir does not require bare mineral soil for regeneration and is tolerant of a wider range of environmental conditions for regeneration compared to ponderosa pine (Hermann and Lavender 1990). Less aggregated regeneration may be expected as a result, although Douglas-fir is sensitive to fire and is still likely to tend toward grouped distributions as regeneration is concentrated in areas that are protected from fire (Steinberg 2002). The safe-site mechanism may be less pronounced on low-productivity sites due to less understory competition and lower resource availability to support trees growing close to one another. A more spatially dispersed structural pattern may predominate on low-productivity sites as a result (Abella and Denton 2009).

In areas where mature tree mortality occurs over larger spatial scales, such as in patches of stand-replacing or high-severity fire, a “safe period” mechanism may be more important to regeneration than safe sites. In this case, regeneration is regulated by the simultaneous availability of mineral soil, a seed source, and adequate soil moisture to support seedling germination and establishment (Huckaby et al. 2001; Kaufmann et al. 2003; Mast et al. 1998). The alignment of these conditions in both time and space is somewhat stochastic and may be rare for many years following patch mortality such as that created by high-severity fire. Thus, openings created by high-severity fire may persist on the landscape for several years to decades, or in other cases may regenerate quickly if nearby seed sources are present.

Understanding regeneration dynamics and site-dependent spatial patterns of regeneration is important as it can inform treatment design for a given site and the degree to which tree groups are ecologically appropriate versus randomly arranged individual trees. Often the site itself will provide clues about historical structure and tree spatial patterns based on the arrangement of old trees, snags, or remnant stumps (see section 3.1). If the site appears ecologically suited to a grouped stand structure, then effort should be made to enhance tree groups to the extent possible. Tree groups should be retained and separated from other groups of trees through the creation of openings. Often, however, complex stand structures have been simplified by past management, leaving little existing spatial heterogeneity with which to work and enhance through restoration. In this case, heterogeneity should be enhanced to the extent possible primarily by creating openings and retaining groups and single trees where possible. Creating openings is also likely to encourage aggregated tree regeneration, which will eventually restore spatial heterogeneity as regenerating tree groups grow into mature trees.

The central idea here is that the spatial pattern of retention influences the spatial pattern of regeneration, and treatments should be conducted with the intent of setting the stand or treatment unit on a trajectory of continued heterogeneity through regeneration processes. The use of managed fire is extremely important here as well, as fire naturally shapes the spatial pattern of regeneration by killing some seedlings and saplings while sparing others. Fire may naturally promote aggregated regeneration in areas that are fire-protected due to landscape features.

Last, in anticipating and planning for regeneration responses, it is also important to consider the spatial arrangement of seed trees. If the goal is to create and maintain openings (i.e., persistent openings), then seed trees should be removed from within the opening. Alternatively, if the goal is to create transient openings for tree regeneration, then seed trees should be retained adjacent to openings. Both situations are likely to occur within a given treatment unit. Species composition is another important consideration, as the species that are present posttreatment are the species most likely to repopulate the site (panel 5).

3.7 Restoration is Based on Locally Derived Ecological Models

The combination of all the factors described earlier—environmental gradients, natural disturbances, and forest developmental processes—historically led to a wide range of forest structures across the Front Range at both landscape and stand scales. A primary goal of this document is to describe this range of variability in forest structure by various physiographic settings to give planners and implementers a sense of the range of structures that may be appropriate for given landscapes and treatment units. We are careful to emphasize that any given site is likely to be characterized by a **range of structures**, and enhancing heterogeneity by incorporating a range of structures is a central goal of restoration treatments (as opposed to retaining trees to a central mean or narrow range in density). We next present a generalized ecological model within which more detail can be developed for factors such as the range of opening sizes and tree group sizes, based on local conditions.

- **Lower montane settings** across the Front Range include areas less than approximately 7,800 feet in elevation on the northern Front Range and about 8,200 feet on the southern Front Range (panel 6; table 6). In lower montane **dry settings**, such as south-facing mid-slopes and ridges, appropriate landscape patches include openings and open-canopy forests (see section 3.3 for definitions of patch types based on canopy cover). Within open-canopy forest patches, a mixture of tree groups, individual trees, and fine-scale openings (<1 acre) are all appropriate structural features. Tree groups are likely to be small in these settings, typically containing two to five trees per group. In lower montane **wet settings**, such as north-facing slopes and lower slopes, appropriate landscape patches include openings, open-canopy forests, and closed-canopy forests. The potential for a broader range of structures may exist in

Panel 5—Species Composition, Silvics, and Implications for Restoration

Ponderosa pine and Douglas-fir are the dominant tree species in lower montane settings of the Front Range and a basic understanding of their silvical characteristics, fire adaptations, and autecology is useful in interpreting historical and current distributions, as well as in anticipating species-specific responses to restoration treatments. Ponderosa pine on the Front Range occurs across a range of soils, from fine- to coarse-textured soils, and can tolerate a wide range of moisture conditions. It is considered highly drought-tolerant and is characterized by a deep taproot that enables access to deep water sources on coarse-textured soils with low water-holding capacity (Minore 1979). Ponderosa pine is shade-intolerant and is often outcompeted by species such as Douglas-fir without regular disturbance such as fire (Minore 1979). Ponderosa pine is also highly fire-tolerant due to its thick bark, tight needle bunches that protect meristems, an open crown growth form, and self-pruning of lower limbs (Fitzgerald 2005; Howard 2003; Kaufmann et al. 2005). Seedlings are generally susceptible to fire, but saplings are often able to survive low-severity surface fire (Battaglia et al. 2009; Howard 2003; Veblen and Donnegan 2005).

Like ponderosa pine, Douglas-fir occurs across a wide range of soil conditions, but it is not as drought-tolerant as ponderosa pine. Along the Front Range, Douglas-fir is most often found on relatively moist sites such as north-facing slopes (Peet 1981). Its incidence on south-facing slopes may increase at higher elevations, concomitant with increases in moisture. Unlike ponderosa pine, seed germination and establishment do not require mineral soil and can occur in the presence of a litter and duff layer (Hermann and Lavender 1990). Seedling growth rates of Douglas-fir, however, are lower than those of ponderosa pine, and traits that confer fire tolerance do not develop until much later compared to ponderosa pine, making juvenile Douglas-fir susceptible to fire for longer time periods (Steinberg 2002).

When restoration treatments are being planned, it is important to consider species composition and species silvics, as posttreatment species composition will influence regeneration dynamics and forest developmental trajectories. In general, ponderosa pine is favored for retention over Douglas-fir in Front Range forest restoration because ponderosa pine is more drought- and fire-tolerant and is therefore probably better suited for withstanding future disturbances and climate change. However, decisions about residual species composition must be site-specific. If Douglas-fir trees (especially old trees) are abundant prior to treatment (most likely on higher-moisture sites), then the site is probably suited to Douglas-fir and Douglas-fir should be retained along with ponderosa pine.

Throughout this document we combine ponderosa pine and dry mixed-conifer forests in our discussion of ecological dynamics, as the two forest types often intermix based on underlying moisture gradients in what is manifested on the Front Range landscape as a continuum of dry coniferous forests. A key distinction between the two forest types, however, is the proportion of Douglas-fir. Dry mixed-conifer forests contain a higher proportion of Douglas-fir compared to ponderosa pine forests. Our recommendations for treatment implementation to meet restoration goals in section 4 are based largely on an Individuals, Clumps, and Openings (ICO) approach to forest management (Churchill et al. 2013a). The extent to which the ICO approach is appropriate for dry mixed-conifer forests is not fully known and should be evaluated through monitoring and adaptive management.

these settings, due to higher soil moisture availability and productivity. Tree groups may also be larger in these settings, on the order of 10 to 20 trees per group. A wide range of opening sizes is appropriate as well, representative of variably sized openings created historically by moderate- and high-severity fire.

- **Upper montane settings** on the Front Range include areas between approximately 7,800 and 9,100 feet on the northern Front Range and between 8,200 and 9,300 feet on the southern Front Range. South-facing slopes and ridges represent relatively **dry settings** at upper elevations as well, with ecologically appropriate landscape patches including openings and open-canopy forests, though very likely with a tendency toward higher canopy cover based on higher moisture availability. A mixture of tree groups, individual scattered trees, and fine-scale openings should all

Panel 6—Elevation Zones and Physiographic Settings of the Front Range

Vegetation on the Front Range changes conspicuously with elevation, leading to early vegetation descriptions by elevation or "life zone." Ramaley (1907), for example, described the Front Range according to four broad elevation zones: foothills (5,800 to 8,000 feet), montane (8,000 to 10,000 feet), subalpine (10,000 to 11,000 feet), and alpine (11,500 to 14,000+ feet). Though modified by various researchers through the years (e.g., Greenland et al. 1985; Marr 1961; Peet 1981; Vestal 1917), vegetation-elevation zones continue to be a useful means of organizing Front Range vegetation types. Many recent studies distinguish between the lower and upper montane zones of the Front Range in describing vegetation as well as historical fire regimes (table 6).

In this document, we use a similar convention in describing vegetation and fire regimes by lower and upper montane settings, but we adjust for latitudinal influences in defining elevational cutoffs between the northern and southern Front Range (Peet 1978). On the northern Front Range, we define lower montane settings as occurring between approximately 5,500 and 7,800 feet in elevation, and upper montane settings as occurring between 7,800 and 9,100 feet. On the southern Front Range, we extend the lower montane boundary to 8,200 feet and define upper montane settings as occurring between 8,200 feet and 9,300 feet. Our definitions are based on literature values provided by various studies on the Front Range (table 6).

Although we use these elevational categories as a way of organizing our discussion of forest types and dominant ecological processes, we emphasize that transitions in forest types and ecological processes do not occur by hard elevational boundaries but rather are dynamic. These transitions are influenced by a host of other environmental factors in addition to elevation (see section 3.4). Elevation should be one of many considerations when evaluating landscapes and determining the forest structures that are ecologically appropriate to that landscape.

We also urge caution in the use of elevational cutoffs in determining whether restoration is warranted or not. In general, the restoration imperative is most evident (and agreed upon) in lower montane settings of the Front Range (FRFTPR 2006). In the upper montane, the overall restoration need may not be present for any given parcel of land (Schoennagel and Nelson 2010); that is, a given location may not be departed from its historical condition for that elevation. However, planners and managers should consider the upper montane landscape in total and the range of patch types that are likely to have been present under an intact fire regime. Perry et al. (2011) discuss what is referred to as "beta diversity" (the diversity among patch types or habitats) as a key feature of mixed-severity fire regimes that has been diminished since Euro-American settlement in many western forests. Lack of beta diversity allows for unimpeded spread of disturbances such as high-severity fire or disease and insect outbreaks. Thus, restoration of landscape patch types may be warranted in upper montane settings where patch type diversity is currently low and would be expected to be higher based on topographic features and historical fire behavior.

be present in these settings. Tree groups in upper montane dry settings are expected to be larger than in lower montane dry settings, probably on the order of at least 5 to 10 trees per group. Upper montane **wet settings** (e.g., north-facing slopes and lower slopes) were very likely historically characterized by a higher proportion of closed-canopy forests, but openings would have been common due to blowouts created by high-severity fire. Open-canopy forests were probably present as well.

In practice, we encourage planners and managers to characterize their landscapes by physiographic settings and the dominant environmental gradients therein, and to evaluate the current distribution and arrangement of structural features relative to what might be expected based on historical dynamics and an intact fire regime. At the treatment scale, planners and managers can "place" their treatment units within the physiographic settings described previously to arrive at the range of ecologically appropriate structures and to suggest which historically common structures could be restored through treatment activities. Under this general framework, however, it is extremely important to allow site-specific factors, such as underlying moisture gradients and presence of historical

Table 6—Elevational ranges associated with lower and upper montane settings on the Front Range.

Setting[a]	Source	Lower montane (feet[b])	Upper montane (feet)
Northern Front Range	Marr 1961	6,000–7,700	8,000–9,000
	Peet 1981	5,900–8,040	8,040–9,350
	Mast et al. 1997	5,905–8,530	NA
	Veblen and Donnegan 2005	5,740–8,040	8,040–9,350
	Kaufmann et al. 2006	5,500–7,500	7,500–9,000
	Sherriff and Veblen 2006	5,900–7,710	7,710–9,350
	Sherriff and Veblen 2008	Less than 6,890	7,220–9,190
	Schoennagel et al. 2011	5,900–7,780	7,870–9,185
Southern Front Range	Donnegan et al. 2001	6,000–7,710	8,005–8,990
	Kaufmann et al. 2006	6,500–8,500	8,500–9,500
Front Range-wide	Williams and Baker 2012a	5,905–8,040	8,040–9,350

[a] See table 2 for definitions of northern versus southern Front Range.
[b] Approximate elevational range in feet.

structural features, to dictate the appropriate forest structures that should be restored at both landscape and treatment scales.

In reality, forest structure on the Front Range is more complex than implied by this physiographic model, but the model provides an example of how planners and managers might arrive at ecologically appropriate forest structures and patch type distributions through a heuristic approach that considers topography, disturbance, and forest developmental processes. In any physiographic setting, it is important to develop an understanding of local environmental gradients and other factors such as fire behavior that contribute to forest structure patterns. For example, low-severity fire was more common historically on gentle, undulating slopes regardless of elevation, whereas mixed-severity fire was more common in steep, dissected topography (Noss et al. 2006; Sherriff et al. 2014). We might therefore expect open-canopy, uneven-aged patch types to develop on gentle slopes where low-severity fire was common historically, whereas patch types in steep or dissected topography may be more variable based on the increased potential for moderate- and high-severity fire (table 5). Restoration is fundamentally about understanding the local ecology and applying that understanding (1) to determine how the forest has come to be in its current condition and (2) to develop desired conditions for restoration that are ecologically appropriate and resilient to future disturbances and climate change.

3.8 Restoration Enhances Important Ecological Processes, Functions, and Ecosystem Services

In addition to managing for desired structural elements as described earlier, restoration should also consider how forest structure patterns at both landscape and stand scales shape ecological processes, functions, and ecosystem services. As stated by Larson et al. (2012: p. 516), "Restoration treatments should aim to restore forest structure to the domain of functional pattern-process linkages that generate and maintain heterogeneity, resilience, and desired ecological functions." The impetus for restoration is often a degraded or undesirable process (such as high-severity wildfire threatening water supplies), yet in many cases the processes themselves are not specifically analyzed and considered when designing restoration treatments (Falk 2006). Restoration objectives should explicitly acknowledge desired outcomes from an ecological process perspective and then work backwards to determine those forest structures that are necessary across scales to facilitate desired processes and ecosystem services (Seidl et al. 2016).

Ecosystem services can be defined simply as the benefits that people receive from ecosystems, often categorized according to provisioning services, regulating services, cultural services, and supporting services (Kremen and Ostfeld 2005; Millennium Ecosystem Assessment 2005). Provisioning services include the actual products we obtain from ecosystems, such as food, fiber, fuel, and water. Regulating services include such services as air and water quality regulation, climate regulation, and natural hazard regulation (e.g., wildfire or flood regulation). Cultural services are nonmaterial benefits we receive from the environment, including recreation, aesthetic experiences, and spiritual enrichment. Supporting services provide indirect benefits to people but are vital to the production of other services through basic ecological processes such as nutrient cycling, photosynthesis, and soil formation.

Some of these ecosystem services are more relevant and valuable than others to the Front Range. For example, wildfire regulation is particularly important on the Front Range. Fire is one of the main ecological processes we hope to influence through forest restoration, primarily by restoring low- and moderate-intensity fire where ecologically appropriate in areas currently susceptible to large-scale high-intensity fire due to high tree densities and continuous canopy cover. Restoration of open-canopy forest patches where ecologically appropriate throughout the Front Range landscape will help to regulate wildfire behavior in desired ways, and may provide increased opportunity for the use of broadcast prescribed fire as well. Restoration objectives as they relate to fire behavior should be clearly stated. Models that link forest structure to fire behavior metrics such as fireline intensity and rates of spread can be used to gain a sense of forest structures necessary to facilitate desired fire behavior (e.g., Ziegler et al. 2017).

Water is a key provisioning service that we also wish to protect through forest restoration on the Front Range (Colorado State Forest Service 2009). Mountainous watersheds of the Front Range provide most of the water supply needed for municipal and agricultural water uses on the Front Range. River systems, reservoirs, and water supply infrastructure such as intakes may all be impaired by the postfire soil erosion and debris flow that often accompany large-scale high-severity wildfire. Watershed assessments should be conducted to determine how much of a given watershed must be maintained in a forested state to avoid negative impacts to water resources (e.g., FRWPDRWG 2009). Coupled fire behavior-soil erosion modeling approaches can be brought to bear in such assessments to identify contributing areas to water resources and analyze potential impacts if those areas were to burn with high-severity fire effects (Miller et al. 2011; Sidman et al. 2015; Thompson et al. 2013; Tillery et al. 2014).

Other important ecosystem services for the Front Range are cultural services, which are important not only to the cultural identity of the Front Range but also to local economies through tourism-based revenue. Provisioning for wildlife and biodiversity are also important, as is maintenance of supporting services such as tree regeneration after wildfire. The key point here is to identify those ecological processes and services important within the landscape of interest and to develop management goals based on them. Treatments at the stand scale can then be located, designed, implemented, and monitored to support those services. For example, in the case of tree regeneration following wildfire, Turner et al. (2013) offer recommendations about enhancing spatial heterogeneity in a way that influences fire behavior patterns and subsequently increases the likelihood of seed tree survival for regeneration by strategically maintaining legacy patches on the landscape. Such an approach would require an analysis of landscape fire behavior and the distribution of patches where low-severity fire is most likely to occur (based on fuels, topography, and weather) to determine if spatial heterogeneity is adequate to support tree regeneration following wildfire. Additional considerations include:

- Spatial connectivity and its influence on the "flow" of ecosystem services, as described by Bagstad et al. (2013a). For example, how might treatments in one part of the landscape affect "downstream" users based on ecosystem services flow paths?
- Tradeoffs and synergies among multiple ecosystem services, as described by Bennett et al. (2009) and Turner et al. (2013). It is important to consider how multiple ecosystem services interact spatially on the landscape and how the broader range of ecosystem services may be affected by management, especially if management is focused primarily on one service such as wildfire regulation. Bennett et al. (2009: p. 399) point out that "[m]anaging relationships among ecosystem services can strengthen ecosystem resilience, enhance the provision of multiple services, and help to avoid catastrophic shifts in ecosystem service provision."

Ecosystem services assessment tools can be brought to bear in the restoration planning process to account for the variety of ecosystem services that may exist within a given landscape (reviewed in Bagstad et al. 2013b; also see Vigerstol and Aukema 2011). These tools may be used to evaluate where tradeoffs and synergies among multiple ecosystem services may be most pronounced. Last, work conducted in the name of ecosystem services may not always be explicitly restoration based, but should incorporate restoration principles wherever possible and be appropriate to the local ecology.

3.9 Restoration Selects for Landscape and Stand Traits That Will Confer Resilience to Climate Change

Enhancing forest resilience to climate change is a primary goal of forest restoration on the Front Range. Forest restoration must therefore continually consider and anticipate potential consequences of climate change for future forest structure, composition, and function, as well as for ecosystem services. Climate change is defined by the Intergovernmental Panel on Climate Change (IPCC) as the "change in the state of the climate that can be identified by changes in the mean and/or variability of its properties and that persists for an extended period, typically decades or longer" (IPCC 2014: p. 120). Factors used to evaluate climate change typically include temperature and precipitation, as well as the intensity and duration of drought (IPCC 2014).

For the Southern Rockies in general, Rocca et al. (2014) highlight trends that are likely to result from climate change:

- Increasing temperatures, leading to a greater proportion of precipitation falling as rain, earlier spring snowmelt, and overall less snowpack;
- More extreme weather events, such as storms with heavy precipitation and periods of drought; and
- A likely increase in the moisture deficit. Models do not clearly show whether total precipitation will increase or decrease; with higher temperatures and more evapora-

tion, however, moisture deficit is expected to increase even if precipitation increases somewhat.

In Colorado, climate change has already resulted in changes in temperature, precipitation patterns, and timing of snowmelt and runoff. The mean annual temperature has increased throughout Colorado by an average of 2.0 °F during the last 30 years, with similar trends for the Front Range (Lukas et al. 2014) (fig. 23). Mean annual temperatures across the State are projected to rise by another 2.5 to 5.0 °F by 2050 (Lukas et al. 2014). The number of growing degree days has also increased over both a 56- and 20-year period evaluated by McGuire et al. (2012). The timing of snowmelt and runoff has shifted 1 to 4 weeks earlier in the spring over the last 30 years. Drought events have become more severe as well (Lukas et al. 2014).

These changes in climate will affect Front Range forests through the influence of climate on reproduction, growth, and survival of forest organisms, and through climatic effects on major disturbances such as fire and insect or disease outbreaks. Of these, the changes in disturbances are likely to have the largest impact on ponderosa pine and dry mixed-conifer forests of the Front Range (Rocca et al. 2014). Specific effects may include:

- Longer fire seasons that could result in more land area burned (Litschert et al. 2012); potential increases in both fire frequency and fire extent as a result of climate-driven shifts in vegetation (Liu and Wimberly 2016);
- Increased tree mortality due to drought (McDowell and Allen 2015), as well as during wildfire events, due to hotter, drier conditions and potential near-term increases in fire severity (Rocca et al. 2014);
- Lack of tree regeneration following wildfire because of unsuitable conditions for regeneration, including warm air temperatures and dry soil conditions that may inhibit seedling germination and establishment (Chambers et al. 2016; Rother et al. 2015);
- Changes in the geographic distributions of species along elevational and latitudinal gradients; movement of drought-tolerant species such as ponderosa pine upslope; conversion to grasslands or shrublands at low elevations (Liu and Wimberly 2016);

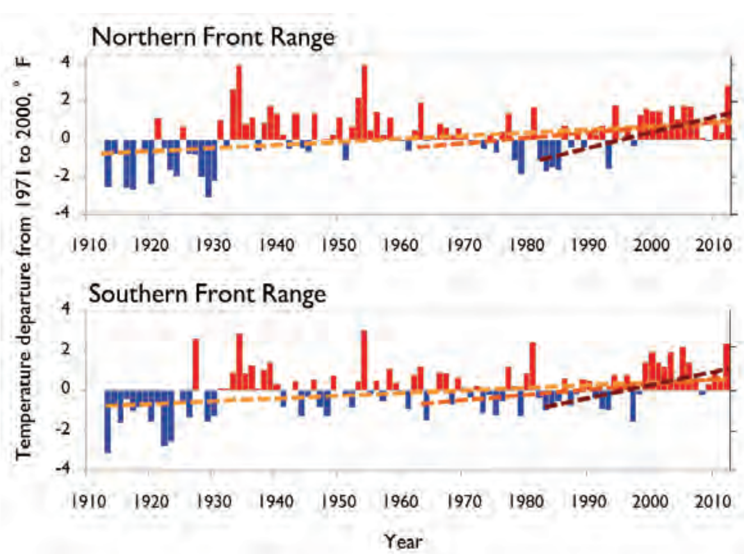

Figure 23—Temperature trends for the northern and southern Colorado Front Range. Data are a composite of annual average daily temperatures from 1913 through 2012 recorded at several stations and expressed as the departure in temperature from the 1971 through 2000 average. Red bars represent above-average temperatures and blue bars represent below-average temperatures. Dashed lines represent linear trends over 100-, 50-, and 30-year timeframes (figure: Lukas et al. 2014, used with permission).

- Increased incidence of insect and disease outbreaks due to lack of cold snaps that typically limit insect and disease activity or due to weakened tree defenses, or a combination thereof (Bentz et al. 2010); and
- Increased interaction of wildfire with the wildland-urban interface due to climate-driven shifts in fire regimes coupled with wildland-urban interface expansion into areas of high wildfire risk (Liu et al. 2015).

Although there is some uncertainty in exactly when and where these effects may be manifested, there is even greater uncertainty about suitable management strategies to address and prepare for climate change (Kemp et al. 2015). Fortunately, a substantial amount of literature has been written in the last decade to provide practical guidance on climate change assessments and the development of adaptation strategies (e.g., Cross et al. 2012; Glick et al. 2011; Janowiak et al. 2014; Peterson et al. 2011; Stein et al. 2014; Swanston et al. 2016; West et al. 2009). Vulnerability assessments in particular offer a useful framework for climate change planning based on three components of vulnerability: (1) sensitivity, or the inherent tolerance or ecological amplitude of a given species to changes in the environment based on life history traits; (2) exposure, or the rate and magnitude of environmental change the species may actually experience; and (3) adaptive capacity, or the ability of a species to adapt along with changes in the environment as they occur (Glick et al. 2011). Vulnerability assessments can then lead directly to strategies focused on enhancing resilience (Janowiak et al. 2014). The Climate Change Response Framework developed among scientists, managers, and landowners in the eastern United States and the upper Midwest, offers tools and techniques for developing climate adaptation strategies (see http://www.forestadaptation.org/).

Much of the guidance already offered in this document is appropriate within a climate-change context, as it is aimed at enhancing overall landscape resilience to disturbance as well as climate change. Thus, it represents a "no regrets" strategy (Joyce et al. 2009) and aligns well with other restoration objectives. Potential strategies specific to climate change, however, may include:

- Enhance heterogeneity across spatial scales in order to increase options for adaptation. Greater landscape diversity increases the likelihood that multiple forest values will persist under future climate and disturbance regimes (Seastedt et al. 2013; Turner et al. 2013).
- Reduce forest densities, especially on drought-prone sites, to reduce competition, site moisture stress, and likelihood of active crown fire (Rocca et al. 2014).
- Reintroduce low- to mixed-severity fire via broadcast prescribed fire where possible to reduce fuel loads and restore fire as a natural ecological process.
- Use vulnerability assessments to identify plant traits that may confer a climate-change advantage (Laughlin et al. 2016; McDowell and Allen 2015); favor drought- and fire-tolerant tree species such as ponderosa pine over less tolerant species (see panel 5).
- Strategically protect seed-tree patches on the landscape, especially near suitable regeneration sites, to increase the likelihood of tree regeneration following wildfire (Turner et al. 2013).

- Maintain and enhance habitat connectivity along latitudinal and elevational gradients to facilitate plant and animal movement in response to climate (Janowiak et al. 2014; McGuire et al. 2016); minimize barriers to migration and consider assisted migration strategies where barriers exist; conduct research to improve our understanding of rates of exclusion of species at their lower elevations relative to rates of migration into emerging suitable environments at upper elevations.
- Identify rare or specialist species with limited geographic ranges; develop specific protection strategies for these species as they may be particularly vulnerable to climate-induced changes in habitat.
- Protect and enhance riparian vegetative cover in order to maintain shade, reduce exposure, and decrease the potential for rising stream temperatures and negative impacts to aquatic environments.
- Develop and maintain rigorous ecological monitoring and adaptive management programs (Janowiak et al. 2014; Lawler et al. 2010; Millar et al. 2007); active adaptive management is particularly appropriate in the context of climate change as it deliberately seeks to address uncertainties in management through experimentation (Larson et al. 2013; Seidl et al. 2016).
- Develop and maintain rapid detection programs for invasive plant and animal species.
- Conduct informational outreach to educate Forest Service staff, stakeholders, and the public about climate change impacts. Evaluate and communicate the real costs of living in fire-prone environments, including the costs of fire suppression and postfire landscape rehabilitation, relative to proactive forest management.
- Promote and reward the development of innovative strategies for addressing climate change impacts; encourage experimentation and research.

Last, it is important to recognize the role of forested landscapes in mitigating greenhouse gas emissions that contribute to climate change. Restoration treatments may enhance the carbon sequestration potential of forests by promoting forest health, vigor, and carbon uptake capacity, and by maintaining carbon stores in old, large trees (Hurteau and North 2009; Hurteau et al. 2008). Prescribed fire may reduce the potential for severe wildfire, thereby reducing the emission pulses that typically accompany large, high-severity wildfire events (Wiedinmyer and Hurteau 2010). Use of forest materials as biofuels can also replace fossil fuel use for energy production where opportunity exists.

3.10 Restoration Follows an Adaptive Management Process and Emphasizes Continual Learning

Current scientific and field-based knowledge about restoring ponderosa pine and dry mixed-conifer forests in the Colorado Front Range has expanded considerably in recent years. However, there remain untested assumptions and uncertainties about restoration outcomes and effects. Adaptive management provides an important framework for restoration, as it describes a discrete set of steps to guide the restoration process and provides a mechanism for learning, reflection, and thoughtful change. As described by Benson and Garmestani (2011: p. 395), adaptive management "recognizes that our understanding of natural systems is constantly evolving and reflects a willingness to test our assumptions about the natural environment in order to adapt and learn." Adaptive management is particularly important in the context of uncertainty as it provides a framework for "learning while doing" and encourages refinement or adjustment of management actions based on outcomes of previous management.

In its simplest form, adaptive management is often represented as a cycle with the key elements of planning, implementation, monitoring, evaluation, and adaptation (Kaufmann et al. 2009). For the Front Range, Aplet et al. (2014) have developed an adaptive management process that depicts these broad elements in more detail and contains several important feedbacks between treatment planning, monitoring, and other aspects of the restoration process. We encourage readers to consult Aplet et al. (2014) for a more detailed description of each of these components, but provide a summary of the broad themes here to set the stage for implementation guidance provided in section 4 of this document.

Identify ecological values, restoration goals, and desired conditions—The planning phase of adaptive management involves careful identification and articulation of the landscape's ecological values (a term referring broadly to ecological processes, functions, and services as described in section 3.8), goals, and desired conditions to be achieved or sustained through restoration. What do we care about most in the forest ecosystems of the Front Range? What are the values that our forests provide and upon which we rely? What are the expected benefits of restoration? Ecological values should be defined early in the restoration process and serve as the foundation for more detailed restoration goals that describe actions necessary to maintain or enhance these values. Desired conditions then describe the physical state of the forest across scales believed necessary to promote desired ecological processes and achieve restoration goals. Basic framing questions for this component of the restoration process may include:

- What is the goal of restoration?
- What is the forest condition necessary to achieve that goal (i.e., the desired condition)?
- What aspects of the forest need to be changed to meet the goal?

Assess current conditions to identify treatment needs and opportunities—The planning phase of adaptive management also involves an assessment process to determine whether current forest conditions differ substantially from historical or desired conditions. This part of the restoration process is necessary to determine whether there is in fact a need for restoration. Assessments should consider current vegetation conditions, as well as areas of special significance, values at risk, and opportunities to create synergies (described in more detail in section 4). Assessments should be aimed at identifying priority areas for restoration (i.e., where work should occur on the ground) to achieve the desired condition, especially in the context of limited resources available for restoration work. This part of the planning process must also evaluate opportunities for restoration treatments based on accessibility, land ownership patterns, financial resources available to develop projects, and landowner engagement and willingness to implement treatments, especially on private lands.

Develop treatment plans and prescriptions—The development of treatment plans should follow the assessment process once needs and opportunities have been identified. This part of the process will involve formulating more specific and measurable management objectives that tier to the broader goals and desired conditions developed earlier in the process. Treatment plans should be developed at both the landscape and stand scales, with consideration of how management activities at the stand scale may "roll up" to the landscape scale to affect landscape processes such as fire behavior. Development of more detailed treatment prescriptions then follows to provide more information about how treatments are to be implemented in order to achieve desired outcomes.

Monitor and adapt—Monitoring is vital to the adaptive management process as it is the only clear means by which managers and stakeholders can evaluate and demonstrate whether the treatments are achieving their objectives—in other words, leading to progress toward the desired conditions. Implementation of management actions should be accompanied by monitoring at several stages, including both before and after treatments. After implementation, management techniques should be reevaluated in light of monitoring outcomes, new information, or changing conditions. This information should be used to determine whether desired outcomes are being achieved and whether adjustments in management strategies are needed.

4. Principles to Practice—A Process for Restoration at Landscape and Stand Scales

Practical application of the principles described earlier can be challenging on the Front Range given the complex social and political contexts within which an already complex ecology occurs. The intent of this section is to offer guidance on the application of principles using a stepwise process that proceeds from the landscape to the stand scale and integrates the ecological information presented previously (fig. 24). We recognize that in many cases agencies and organizations have their own planning frameworks and what we present next is not intended to supplant existing agency-specific planning approaches. Rather, we are intentionally broad in our description in order to complement existing planning frameworks. As with any framework, the user is encouraged to modify the individual components to fit the needs of specific organizational, social, or political contexts that may be present.

4.1 Step 1: Identify Ecological Values, Restoration Goals, and Desired Conditions at the Landscape Scale

Ecological values at the landscape scale form a central basis for the restoration effort, as restoration is often not an end unto itself but rather a means to maintain desired ecological processes and ecosystem services. Ecological services supported by restoration on the Front Range will most often include water, wildlife, biodiversity, and resilience to disturbances and climate change (see section 3.8). Restoration is expected to protect and enhance these values by increasing landscape heterogeneity and reestablishing a low- to mixed-severity fire regime. With respect to water, for example, restoration is expected to reduce the potential for the severe soil damage, postfire soil loss, and debris flow that can result from high-severity fire, thereby protecting water resources from these impacts. Similarly, restoring fire in parts of the landscape where it has been rare or missing can enhance habitat for rare wildlife species such as the northern goshawk that rely on ponderosa pine and dry mixed-conifer forests of the Front Range.

Once broad ecological values are identified for specific landscapes, restoration goals should be developed to provide more detail about what restoration will do to protect or enhance the ecological values. Restoration goals will form the basis of assessment processes aimed at identifying more specific needs and opportunities for restoration work. Goals of landscape-scale forest restoration may include:

- Enhance landscape resilience to natural disturbances and climate change;
- Sustain important ecosystem services for human welfare;
- Protect values at risk from uncharacteristic disturbances or unintended consequences of management or land uses;
- Reduce the potential for broad-scale, active crown fire, which results in large patches of tree mortality;
- Create vegetation structure patterns that will allow natural disturbances to operate at characteristic scales and intensities without socially or ecologically undesirable consequences;

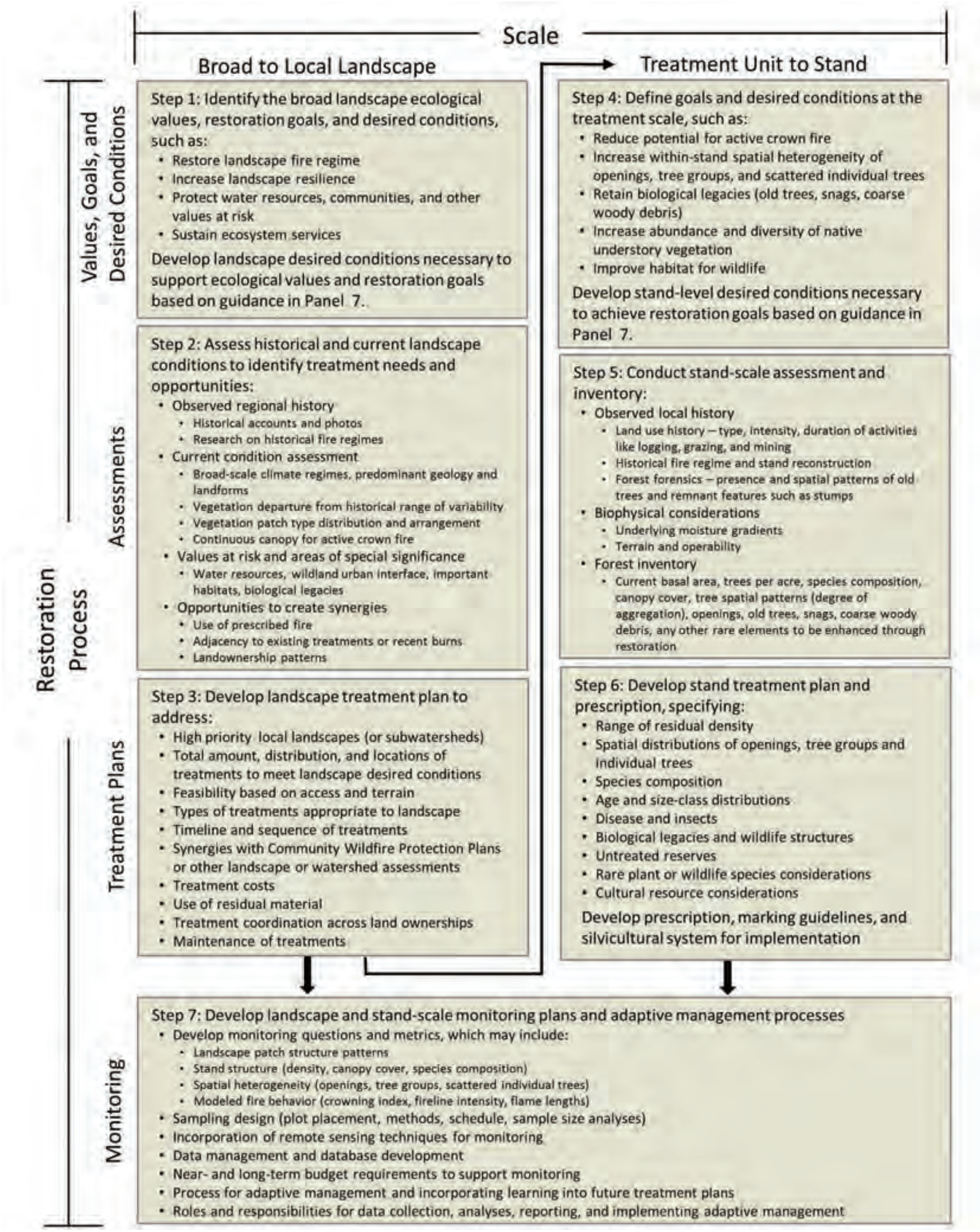

Figure 24—Components of the restoration process across scales.

- Provide ecological benefits for wildlife;
- Increase native biodiversity; and
- Protect rare plant and animal species.

Desired conditions at the landscape scale should then be developed to describe expected patterns of vegetation and the spatial arrangement of various patch types based on topography, disturbance regimes, and forest developmental processes, as described in section 3. Dickinson and SHSFRR (2014) provide more information about desirable forest structures that can be used in developing landscape-scale desired conditions (panel 7).

Panel 7—Desired Conditions for Forest Structure and Composition Across Scales

Desired conditions describe expected patterns of vegetation and the arrangement of various patch types based on topography, disturbance regimes, and forest developmental processes. Dickinson and SHSFRR (2014) identified the following desirable patterns in landscape and stand structures for the Front Range, based on an assessment of current forest structures:

Landscape Scale

- Open, low-density forest patches and openings occur on south-facing slopes, on ridges, and at lower elevations.
- Higher tree densities occur on north-facing slopes, at higher elevations, and in draws and drainages.
- Larger patches (forested or open) occur at higher elevations with mixed-conifer forest types (tens to hundreds of acres) dominating, in contrast with smaller patch sizes at lower elevations, where ponderosa pine forests dominate.
- Larger patches (forested or open) occur on north-facing slopes compared to south-facing slopes.
- Larger patches (forested or open) occur on steep topography; however, where the topography is highly dissected, substantial topographic breaks restrict patch size.
- Landscapes have a very large number of small (<10 acres) patches that cumulatively occupy less than half of a watershed, and a few large patches that occupy half or more of the watershed.
- Both even- and uneven-aged forest patches exist across the landscape; however, there is a predominance of uneven-aged patches, characterized by a range of tree sizes and ages.

Stand Scale

- Openings, groups of trees, and single isolated trees are all present within stands; the proportion and size of openings, groups, and single trees vary within and among stands.
- On low-productivity sites (generally drier sites at lower elevations or south-facing slopes, or both), there is greater prevalence of openings and single isolated trees; ponderosa pine is the dominant tree species.
- On higher-productivity sites (generally with higher moisture availability at higher elevations or north-facing slopes, or both), there is greater prevalence of larger tree groups with fewer openings and isolated trees; ponderosa pine is still the dominant species but co-occurs with Douglas-fir.
- The proportion of trees in groups varies from stand to stand, ranging from 0 to 80 percent of trees in groups. However, most stands across the landscape have 30 to 60 percent of trees in groups. Groups range in size from 2 to 20 trees, with larger groups on more productive sites. On most sites the median tree group size is small (two to three trees per group).
- Stands contain old trees, snags, and downed wood that lend stand complexity and habitats for wildlife.

4.2 Step 2: Assess Landscape Conditions to Identify Treatment Needs and Priorities

As ecological values, restoration goals, and desired conditions are developed, an assessment process should be initiated to characterize the current condition of the landscape and identify opportunities for treatment. The three components of the assessment process described next are: (1) **current vegetation condition assessment** to identify treatment needs, (2) **values at risk assessment** to identify features that should be protected, and (3) **opportunity assessment** to identify treatment feasibility and the potential for treatment leverage and scalability.

4.2.1 Current Vegetation Condition Assessment

Evaluating the current vegetation condition and the degree of departure from reference or desired conditions is an important first step in the assessment process. The goal of this part of the assessment process is to categorize various landscape vegetation patch types so that current landscape conditions can be compared against historical or desired conditions in order to identify restoration needs (Romme et al. 2012) (panel 8). General framing questions include:

- How different is the current forest structure and composition from historical or desired conditions?
- How did the current condition develop? Is it a result of fire exclusion or other human influences that can be reversed?
- Are there undesirable aspects of the current condition, such as large contiguous areas of closed-canopy forest that present a wildfire hazard?
- Are there features that we would expect to be present that are not; in other words, are there underrepresented features? Underrepresented features often include openings and open-canopy forest patches, as well as spatial heterogeneity in different forest patch types.
- Are different patch types arranged in a way that is spatially desirable and in proportions expected based on historical disturbance regimes and environmental gradients?
- Is the landscape restorable? Can desired conditions realistically be achieved through forest management-based landowner objectives and operability constraints?

Addressing these assessment questions should logically begin to point to both the need and opportunity for restoration if they exist in the landscape. For example, if the landscape is composed primarily of continuous, closed-canopy forest patches, then there is very likely a need and opportunity for restoring open, low-density forest patches and openings, as well as enhancing the spatial distribution of patch types. The landscape can be characterized by vegetation patch types (corresponding to the patch types described in section 3.3) as follows:

- **Openings—**Proportion of the landscape with less than 10-percent canopy cover.
- **Open-canopy forest patches—**Proportion of the landscape with 10- to 40-percent canopy cover, containing mid- or late-seral structural elements, or a combination of both.

Panel 8—Forest Structure Patterns Indicative of Historical Fire Regimes

Current forest structure patterns as well as legacy features such as old trees can provide clues about historical forest structures and fire regimes. It is important to assess these features to determine whether restoration is warranted for a given area, as well as to inform the development of treatment plans. Assessment methods for approximating historical forest structure may include:

- At the landscape scale using aerial imagery, canopy cover maps, or both, look for **misalignment of forest structure with topography**. Low-severity fire was most likely the driving disturbance in the lower montane and on gentle slopes equal to or less than 4° in the upper montane (Sherriff et al. 2014). The presence of dense forest structures in these areas may signal a need for restoration.
- At the stand scale, **multi-aged stand structures** are indicative of a historical low-severity fire regime. The presence of numerous small-diameter trees (less than 4 inches in diameter at breast height) within a multi-aged stand is also indicative of fire exclusion (Sherriff and Veblen 2007).
- An abundant **understory herbaceous vegetation** layer often develops in areas that experience frequent fire. Look for a diverse mix of grasses, sedges, and forbs in the understory (see Keith et al. 2010 for indicator species of Front Range fire regimes).
- Look for the **presence of old trees** that predate Euro-American settlement (circa 1860) on the Front Range. Old presettlement trees often have flattened crowns, thick branches, large bark plates, and deep fissures (Huckaby et al. 2003a). If possible, core a subset of old trees on a given site using an increment borer and count the tree rings to get a rough estimate of tree age locally.
- Evaluate the **spatial pattern of old trees** and the extent to which they occur in groups versus as isolated individuals to gain a sense of historical spatial heterogeneity to inform the development of treatment prescriptions.
- Similarly, look for the **presence of presettlement standing dead trees** (snags) and other historical features such as legacy stumps from Euro-American settlement logging (fig. 25), old downed logs, or other remnant material on the ground. Evaluate the spatial pattern of these historical features as well.
- Look for and tally the **number of fire-scarred trees**. The presence of numerous trees with multiple fire scars indicates a higher historical fire frequency compared to areas lacking fire- scarred trees or having only a few individual trees with single fire scars as opposed to multiple fire scars. Tallying the number of trees with single scars versus those with multiple scars is particularly useful to gain a sense of historical fire return intervals and their associated scale. The presence of numerous trees with multiple fire scars indicates a higher fire frequency (Sherriff and Veblen 2007).

Figure 25—Remnant stump within a ponderosa pine woodland. Stumps such as this can be found throughout Front Range ponderosa pine and dry mixed-conifer forests and provide clues to historical stand structure and spatial patterns (photo: A. Cheng, Colorado State University, used with permission).

- **Closed-canopy forest patches—**Proportion of the landscape with more than 40-percent cover, containing mid- or late-seral structural elements, or a combination of both.

Canopy cover data obtained through remote-sensing databases such as the National Land Cover Database (NLCD) or LANDFIRE (Rollins 2009) can be used for this purpose (fig. 26). Results from this phase of the assessment should provide planners with the relative amounts and spatial distributions of the different patch types, which will enable a determination of what is most prevalent versus what is rare in the landscape. Information from this part of the assessment process can then be used to derive quantitative objectives that specify desired amounts and spatial distributions of the different patch types. It may also be beneficial to apply landscape fire-behavior models (e.g., FlamMap; Finney 2006) to evaluate predicted fire behavior across the landscape. Model outputs such as flame lengths and crown-fire potential can help to identify where on the landscape large areas of tree mortality might occur. These areas may be candidates for restoration activities,

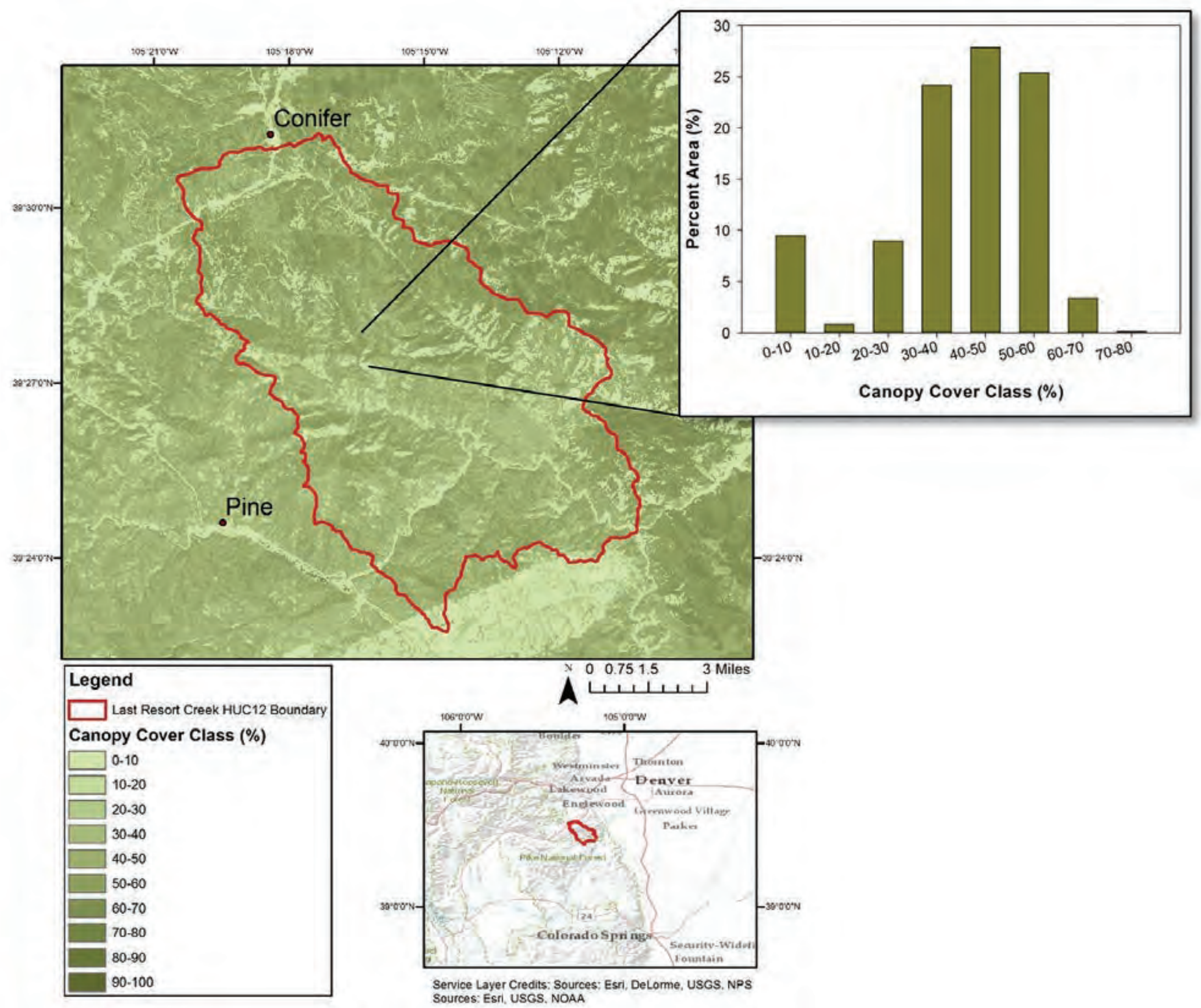

Figure 26—Distribution of canopy cover classes within the Last Resort Creek subwatershed of the Upper South Platte watershed. Most of the area is in medium-density forest structures (40–70 percent canopy cover). The goal of restoration is to shift the distribution toward openings and low-density forest structures where ecologically appropriate, as well as retain some high-density forest structures because they are also underrepresented.

depending on topographic and moisture conditions, forest structure patterns, and tree species composition.

4.2.2 Assessment of Values at Risk and Areas of Special Significance

Landscapes should next be evaluated to determine whether there are values at risk or areas that deserve special protection, either through treatment, special treatment practices, or avoidance of treatment. In each case, locations should be identified within the landscape and mapped to facilitate planning of restoration treatments. Specific considerations include (1) wildland-urban interface, (2) water resources, (3) important habitats, and (4) biological legacies.

Wildland-urban interface—Values at risk within the wildland-urban interface may include homes and important infrastructure. Fuels reduction may be a primary management activity in these areas, especially within the Home Ignition Zone (Calkin et al. 2014; Cohen 2000), to reduce structural ignitability, though restoration principles should be applied when and where possible in this context as well (panel 9). Spatial layers representing the wildland-urban interface can be obtained through databases such as the Colorado Wildfire Risk Assessment Portal maintained by the Colorado State Forest Service, as well as the buildings location database maintained by the Colorado Forest Restoration Institute at Colorado State University (Caggiano et al. 2016).

Water resources—Water resources such as rivers, streams, and reservoirs warrant special protection from high levels of postfire sediment and debris. Important water resources for both municipal drinking supplies and aquatic habitats should be mapped and protected to the extent possible. Upstream or upslope areas that may contribute high amounts of sediment (based on topography, soils, and stream networks) can be identified and mapped using geographic information system (GIS) tools such as the Automated Geospatial Watershed Assessment tool (Miller et al. 2007) or the Geo-spatial interface for the Water Erosion Prediction Project (GeoWEPP; Renschler 2003).

Important habitats—Restoration efforts should focus on areas where restoration will protect, maintain, or expand terrestrial and aquatic habitats, especially for threatened, endangered, and uncommon animal and plant species. Review of species recovery plans and consultation with appropriate wildlife agencies are recommended for rare or Federally listed species.

Biological legacies—Biological legacies include landscape features that persist following disturbance events and that add landscape complexity (Franklin 1989; Franklin et al. 2002). Old trees and old-growth forests represent a special case of a rare landscape element that may warrant special attention to restore a fire-resilient forest structure to protect the forest patch from future fires. Anchoring treatments to known old-growth forest patches can help to expand the desired characteristics to adjacent areas while reducing the risk of disturbance to the old-growth patch.

4.2.3 Identifying Opportunities to Create Synergy

The efficiency and success of restoration treatments may be influenced by the juxtaposition, size, and spatial arrangement of treatments relative to functional landscape features (e.g., natural fuel breaks), other management actions or natural disturbance events, and land ownership patterns. Assessments should identify opportunities to generate synergies

Panel 9—Fuels Reduction Versus Ecological Restoration—Where is Restoration an Appropriate Management Goal on the Front Range?

Fuels treatments focus on changing forest structure and fuels in ways that reduce wildfire hazard and the potential for active crown fire. Fuels treatments often involve removing ladder fuels, reducing the loading and continuity of surface fuels, increasing canopy base heights, and increasing the spacing between tree crowns; they are often accomplished by mechanical thinning, mastication, prescribed fire, or some combination thereof (Agee and Skinner 2005; Cochrane et al. 2012; Graham et al. 2004; Hudak et al. 2011). Although fuels treatments may be effective in modifying fire behavior, they are often singularly focused and may result in evenly spaced trees and structurally simple stand conditions that do not reflect historical variation in stand structures and spatial patterns (Larson and Churchill 2012).

Fuels reduction is often an outcome of ecological restoration as well, though restoration typically involves additional objectives and focuses on restoring complexity and heterogeneity and enhancing features that are currently missing or rare on the landscape today that were present historically. Fuels reduction and restoration are not mutually exclusive. Both approaches have a place on the Front Range landscape (Platt et al. 2006), and planners and managers should consider ways in which they may complement one another on the ground. For example, within the wildland-urban interface, fuels reduction may be a primary management activity near homes (e.g., within the Home Ignition Zone) (Cohen 2000), but restoration principles can also be applied within this context where possible to achieve benefits beyond hazard fuels reduction. The larger landscape matrix between homes is well-suited to a restoration-based approach as well (fig. 27).

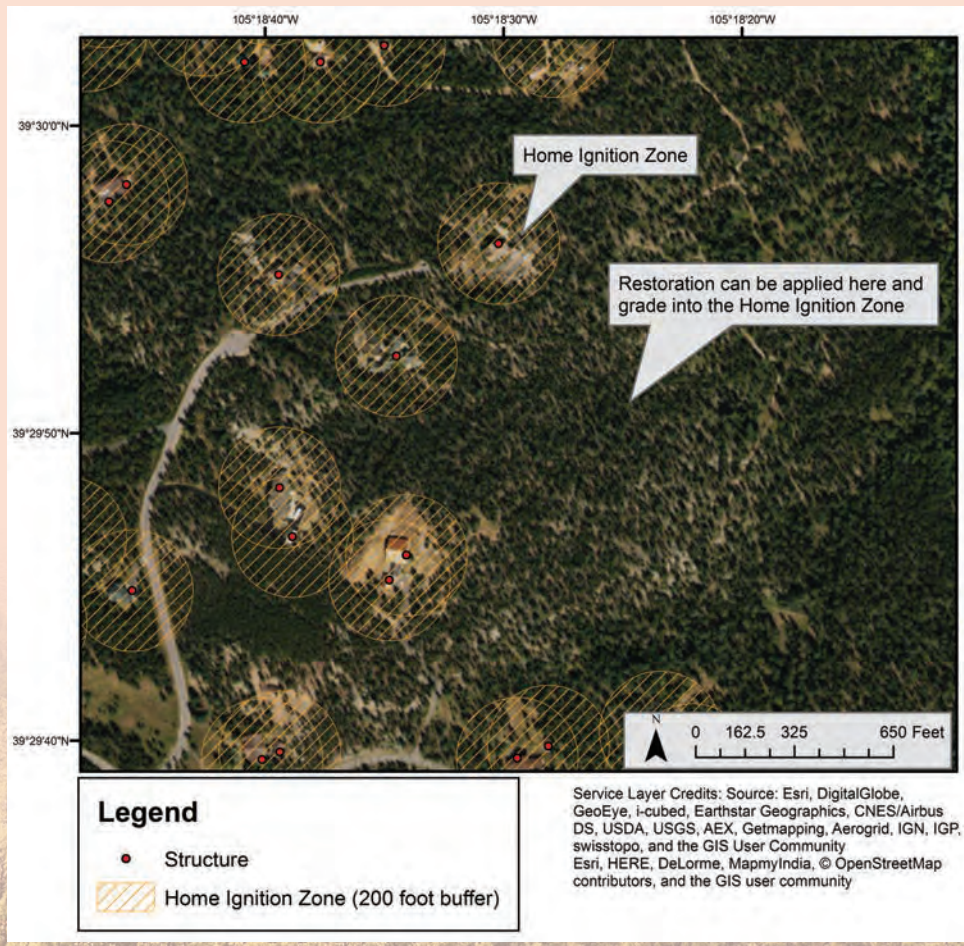

Figure 27—Aerial map showing where restoration could be applied within the wildland-urban interface and how it might grade into the Home Ignition Zone, defined as approximately 200 feet around structures (Cohen 2000).

within this broader landscape context. Landscape restoration should be designed with the following opportunities in mind:

- **Opportunities for achieving multiple objectives—**Identify opportunities to accomplish multiple objectives such as fuels reduction, wildlife habitat improvement, stand improvement, and noxious weed reduction. Achieving multiple objectives through treatments may increase access to funds and partnerships.
- **Opportunities for the use of fire—**Identifying areas on the landscape where fire may be reintroduced through prescribed fire or wildfire management, or both, is important in landscape planning, as these areas offer opportunity to reestablish a keystone ecological process as well as leverage mechanical treatments and efficiently expand overall treatment footprints (North et al. 2012) (fig. 28). Natural fire breaks such as water bodies and rock outcrops should be identified through landscape assessments to identify areas where fire may be used safely.
- **Recently burned areas—**Areas within and next to recent low- and mixed-severity wildfires in ponderosa pine and dry mixed-conifer forests constitute a prime opportunity for forest restoration. Restoration efforts should capitalize on desirable landscape and stand structures created by wildfire to allow large areas of desirable forest patterns to be achieved more efficiently.
- **Land ownership patterns—**Evaluate patterns of land ownership to gain a sense of scalability of the restoration work. For example, are there single private landowners that own large portions of the landscape, or is the landscape subdivided into relatively small parcels (e.g., <25 acres) owned by numerous private landowners? Large parcels with few landowners are likely to facilitate treatment of large, contiguous patches compared to small parcels made up of many landowners. Homeowners associations may also provide an important mechanism for developing synergies

Figure 28—Prescribed fire in the Manitou Experimental Forest on the Pike National Forest, October 2014. Reintroduction of fire through prescribed or wildland fire use is a vital component of restoration as it goes beyond structural restoration to restore ecological processes (photo: S. Alton, U.S. Forest Service).

among groups of landowners, especially in the wildland-urban interface where housing densities are high. Collaborating with other landowners and resource managers to identify common goals and approaches may make it easier to treat larger areas.

- **Networks of restored forests—**Identify opportunities for creating corridors and connections between areas that have been previously treated to broaden the overall treatment footprint. Through time with sustained investments and strategic planning, treatments across the Front Range landscape will begin to add up to a significant scale, with a meaningful influence on landscape fire behavior, forest structure patterns, and other ecological processes.

Most of the criteria just outlined are spatially explicit and mappable, so they can be incorporated within GIS to evaluate overlap and to identify areas where multiple goals may be achieved. This may be done simply through weighted or nonweighted overlays within GIS, or may make use of more sophisticated decision support systems and optimization models that have been developed specifically for this purpose. Examples are the Ecosystem Management Decision Support system (Hessburg et al. 2007a; Reynolds and Hessburg 2005), the Landscape Treatment Designer (Ager et al. 2012), and the ArcFuels package of fuels and restoration planning tools (Collins et al. 2010; Vaillant et al. 2013).

4.3 Step 3: Develop a Landscape Treatment Plan

Assessment criteria described earlier will not only identify treatment needs and opportunities but also begin to point planners toward specific locations on the ground where treatments might occur to meet landscape restoration goals and achieve desired conditions. As these opportunities are identified more specifically, a landscape treatment plan should be developed to provide more detail on the actual restoration approach at the landscape scale. Key framing questions for a landscape treatment plan may include:

- How much of the landscape needs to be treated to meet restoration goals and achieve the desired landscape condition?
- What types and levels of treatments are appropriate to the landscape? Mechanical treatments, hand-thinning, and prescribed fire may all be treatment possibilities on the Front Range. Treatment of residual fuels generated from the treatment itself should also be addressed at the landscape scale.
- Are there forest types such as lodgepole pine within the landscape where the restoration imperative may not be present but where fuels reduction may be appropriate to facilitate prescribed fire and the restoration of nearby dry forest types?
- Are there areas where treatments are needed to protect rare or unique landscape components?
- How will treatments be implemented across land ownerships? What partnerships are needed to implement treatments in a coordinated manner across ownerships and property boundaries?
- How much will treatments cost, and what types and levels of funding will be necessary to implement them across the landscape?
- What are the timeline and sequence of treatments?

- How will treatment effectiveness be monitored at the landscape scale?
- How will treatments be maintained into the future to extend treatment longevity and efficacy?
- How will the treatment plan be adjusted based on landscape-scale monitoring and movement toward or away from desired conditions as treatments progress? Similarly, how will the treatment plan be adjusted in the face of an unforeseen disturbance event such as an insect or disease outbreak, or a wildfire event?

This set of general questions may then lead to a more detailed landscape prescription that specifies the actual number of acres or proportion of the landscape to be treated, as well as the distribution of treatments across the landscape by different treatment types (Collins et al. 2010). Optimization models can help in determining where to treat within the landscape to maximize multiple objectives with budget constraints (Ager et al. 2013; Wei 2012; Wei et al. 2008). These models also enable an evaluation of tradeoffs associated with treatment decisions and treating certain parts of the landscape versus others.

Note that a feasibility assessment is also an important part of landscape treatment planning to identify areas that are accessible based on terrain and existing road networks versus those areas that are not easily reached. A slope of 35 to 40 percent is often considered the cutoff for areas where ground-based mechanical treatment can be used effectively (North et al. 2015). While feasibility is a necessary consideration when planning restoration treatments, we encourage planners not to rule out areas that are more difficult to reach, especially if those areas exhibit the greatest restoration need. Other forms of treatment such as cable or helicopter logging, hand-thinning with sawyer crews, or broadcast prescribed fire, or a combination, should be considered for areas that are difficult to reach but are a high priority for restoration.

4.4 Step 4: Define Goals and Desired Conditions at the Stand Scale

Once a plan is in place for where and how much area should be treated at the landscape scale, a similar assessment and planning process is necessary at the treatment unit or stand scale. This part of the process should likewise begin by identifying broad goals and desired conditions. Goals at this scale should tier to goals at the landscape scale but should be more specific to stand-scale features such as tree groups and openings. Goals at the stand scale may include:

- Reduce the potential for large patches of high-severity, stand-replacing fire;
- Increase stand-scale resilience to natural disturbances and climate change;
- Protect human and ecological values at risk and sustain important ecosystem services;
- Increase within-stand spatial heterogeneity, focusing on spatial patterns of openings, tree groups, and scattered individual trees, to facilitate characteristic fire and sustain biodiversity;
- Retain and enhance foundational features such as old trees, snags, downed wood, and other biological legacies at desirable levels to lend overall stand complexity and provide value for wildlife;

- Protect and conserve rare plant and animal species to benefit biodiversity; and
- Increase or maintain the abundance and diversity of native wildlife species associated with ponderosa pine and mixed-conifer forests.

Desired conditions at the stand or treatment scale then describe expected proportions and spatial arrangements of different stand-scale structural elements (corresponding with features described in section 3.3). Dickinson and SHSFRR (2014) provide more information about desirable forest structures that can be used in developing stand-scale desired conditions (panel 7).

4.5 Step 5: Assess Current Conditions at the Stand Scale

Once goals and desired conditions have been articulated at the stand scale, individual treatment units should be assessed to determine the management approach necessary to achieve the goals and desired outcomes. This is most often accomplished through a pretreatment forest inventory, which commonly includes a combination of aerial image evaluation and an on-the-ground forest inventory. Aerial images can be obtained through publicly available databases such as the National Agriculture Imagery Program or Google Earth® and used to characterize existing patterns of tree density, spatial heterogeneity, and species composition (to the extent that individual species can be discerned from aerial imagery). Standard, plot-based forest inventories are conducted to characterize current conditions and direct treatment prescriptions. Measurements may include basal area, tree species composition, tree diameters, crown base height, surface fuels (using Brown's transects [Brown et al. 1982] or photoloads), and understory plant functional groups. These data can be used to derive overall stand density expressed as basal area and trees per acre, tree species composition, tree diameter distributions, and potential fire behavior and effects using operational fire behavior models. Ideally, data collected as part of a pretreatment inventory can also serve as pretreatment monitoring (see step 7). If used for long-term monitoring, plots should be permanently monumented so that they can be revisited for posttreatment sampling. Field-based measures of historical structures can also accompany the pretreatment inventory to provide information about historical forest structure patterns, as well as historical fire regimes (panel 8).

4.6 Step 6: Develop Treatment Plans and Prescriptions at the Stand Scale

Information from assessment and inventories leads to the development of more detailed management objectives, treatment design criteria, and a treatment prescription. Management objectives should specify:

- A range of basal area, trees per acre, and species composition distributions remaining after treatment;
- Proportion of the treatment area in scattered individual trees and aggregated tree groups;
- Range of the number of trees in groups and distance between groups;
- Desired age- and size-class distributions for residual trees;
- Retention of old trees and character trees;

- Target number of snags per unit area and amount of downed wood;
- Desired cover, abundance, and diversity of understory plants; and
- Target metrics for fire behavior, such as flame length and crown fire potential in the event of wildland or broadcast prescribed fire.

The treatment prescription itself should then be developed to describe in detail how the treatment will be implemented to meet management goals and achieve the desired conditions. Common elements of a treatment prescription may include (1) density, (2) spatial distribution, (3) species composition, (4) age and size distribution, (5) understory vegetation, (6) insects and pathogens, (7) snags, downed wood, and wildlife habitat structures, and (8) untreated reserves.

Density—Density reduction is a key objective of restoration treatments for Front Range ponderosa pine and dry mixed-conifer forests, and density targets should be specified within the treatment prescription. Residual densities should vary both within and among stands based on local variation in environmental gradients. For example, openings and low-density structures are appropriate along ridges and south-facing slopes and should grade downslope into higher density structures. Treatments can be divided into basal area (BA) categories (e.g., open = <20 square feet/acre BA; low density = 20 to 40 square feet/acre BA; medium density = 40 to 60 square feet/acre BA; and high density = 60 to 80 square feet/acre BA), but the percentage of area in each density category within the stand should be variable and reflect moisture gradients and other factors that influence productivity (Appendix B). Developing a target residual density is essential to the prescription process, but the key is to have variability. For example, if the overall target density is 40 square feet/acre BA following a treatment, plots in the treated stand should have BA varying from 0 to greater than 100 square feet/acre, rather than each plot being close to 40 square feet/acre BA after treatment.

Spatial distribution—The treatment prescription should provide information about desired spatial heterogeneity and the mosaic of individual trees, tree groups, and openings (fig. 29). The proportion of trees in groups and group size will be influenced by existing stand conditions, but most tree groups will probably contain 2 to 5 trees with some groups containing as many as 20+ trees. Openings should be highly variable in shape and size, ranging anywhere from 0.25 acre to several acres. Suitable locations for openings may include low-productivity areas such as on shallow soils, areas currently lacking ponderosa pine, areas of disease or insect infestation, and areas where tree regeneration may be desired. Removal of Douglas-fir seed trees near openings may be important to discourage regeneration of this species. Patches of higher tree density would be expected in moister areas such as north-facing slopes and on slope bottoms, particularly where Douglas-fir historically dominated.

Species composition—In areas where ponderosa pine was dominant in the past and is present today, it is generally the preferred species to retain due to its tolerance of drought and fire. Its thick bark, infrequent seed production, and shade intolerance are preferred to maintain more open forest structures over time. Douglas-fir should usually be targeted for removal where it competes with ponderosa pine. In ponderosa pine stands with little or no evidence of Douglas-fir historically, all or nearly all Douglas-fir should be removed. Douglas-fir is a natural component of the Front Range, however, and indiscriminate removal should not be a management objective. Douglas-fir should be retained in areas of

Figure 29—Trumbull restoration unit in the Pike National Forest. This unit was treated in 2002 and is an early example of a treatment that incorporated spatial heterogeneity on the Front Range (photo: P. Fornwalt, U.S. Forest Service).

higher moisture availability, such as slope bottoms and north-facing slopes, particularly where there is little evidence of the historical presence of ponderosa pine. If aspen is present but poorly represented, it should be protected and “day-lighted” (cleared around) to encourage its regeneration. Similarly, Rocky Mountain juniper can be retained on dry slopes where it is often found, but should be removed if it is growing underneath ponderosa pine trees to reduce ladder fuels.

Age and size distribution—Treatments should remove overrepresented age and size classes (usually trees 50 to 120 years old) while retaining old trees (>150 years old) and creating conditions favorable for tree regeneration. A balance of age and diameter distributions is a desired outcome. For example, relatively flat, bimodal, or shallow reverse-J diameter distributions are acceptable posttreatment, as opposed to a steep reverse-J distribution. The eventual goal is to increase the amount of basal area in old, large ponderosa pine trees compared to current conditions. Small-diameter trees and ladder fuels near old trees should be removed to decrease competition and reduce the likelihood of crown fire. If old trees occur in groups, the groups should be retained, as mentioned earlier.

Understory vegetation—Carr and Krueger (2011) emphasize the need to incorporate desired outcomes for understory vegetation directly into treatment prescriptions so that stand structure can be modified in ways that benefit the understory environment. They point out the importance of the understory vegetation layer for numerous ecological processes, including nutrient cycling, soil stability, hydrology, forage for wildlife, and maintenance of a low-severity surface fire regime. Restoration of the understory may in fact be one of the most important components to overall ecosystem restoration, but it is often overlooked in the treatment planning process (Carr and Krueger 2011). Understory vegetation is expected to respond positively to most restoration treatments due to the increase in available resources such as light that accompanies overstory removal

Figure 30—Diverse herbaceous understory at the Manitou Experimental Forest on the Pike National Forest (photo: P. Fornwalt, U.S. Forest Service).

(Abella and Springer 2015; Ertl 2015; Kovacic et al. 1985; Moore et al. 2006) (fig. 30). Following mechanical treatments with broadcast prescribed fire where possible is particularly important in stimulating the growth and reproduction of fire-adapted graminoids, forbs, and shrubs in the understory. Understory vegetation response to treatments may not be evident for several years and may be influenced by climate patterns as well, with higher precipitation often leading to a more vigorous understory response after treatments (Briggs et al. 2017). Noxious weeds and other undesirable understory species may need to be treated before restoration treatments, and should be monitored following treatments.

Insects and pathogens—Areas affected by forest insects or pathogens can provide opportunities for forest managers to create openings. Where the severity and extent of these disturbances exceed the estimated historical levels (see section 3.5), removal of affected trees is usually desired. Although dwarf mistletoe and its resulting brooms can represent important components of individual trees and the forest ecosystem (Bennetts et al. 1996), large areas of dwarf mistletoe infection may require managers to remove infected trees and create openings within the stands to reduce further spread. Areas affected by mountain pine beetle must be evaluated before treatments to ensure that diversity of species and size classes is considered and maintained within the stand (Negrón and Popp 2004). Restoration treatments in these areas should retain some less susceptible trees (e.g., nonhost trees and trees smaller than 4 inches in diameter at breast height) to ensure future forest cover where desired. It is also important to recognize that pathogens and insects are natural components of Front Range forests and are important for snag recruitment. The goal of restoration, therefore, is not to sanitize stands, but rather to strike a balance between snag recruitment and excessive mortality that may be undesirable and inconsistent with historical dynamics.

Snags, downed wood, and wildlife habitat structures—Restoration treatments should retain snags and partially dead trees, especially where these elements of forest structure are locally deficient. Snags are particularly important for wildlife such as bats and cavity-nesting birds (Binkley et al. 2007; Franklin 1989; Reynolds et al. 1985). Logs and other downed wood on the ground surface are also important structural features that add ecosystem complexity and texture, as well as provide cover and refugia for wildlife such as small mammals, reptiles, and invertebrates (Maser et al. 1979; Pilliod et al. 2006), and contribute to key ecological processes such as decomposition and nutrient cycling. A delicate balance is nonetheless needed between these ecological features and fire hazard. Scattered large logs can represent desired features, but piles of logs and slash, or excessive buildup of finer fuels on the forest floor, are generally considered hazardous in the event of an ignition. Some agencies specify guidelines for the retention or creation of wildlife habitat features such as snags and logs (and more specific elements such as Abert's squirrel nest tree clumps), and state the frequency at which these features should occur to provide adequate habitat for wildlife species of concern on their lands (e.g., USDA Forest Service 1984). Without such guidelines, managers are encouraged to plan for as great a diversity and abundance of wildlife habitat features as possible that reflect or simulate the effects of ecological disturbances such as wildfire and insect infestation, and are compatible with fire hazard mitigation and public safety objectives in the areas they treat.

Untreated reserves—Many stands will contain areas that will be left untreated. These areas are often referred to as "skips" and may include ecologically important features such as high-density tree groups for wildlife, wetlands, or regeneration neighborhoods (Franklin et al. 2013; Pilliod et al. 2006). But untreated areas should not compromise the efficacy of the overall restoration treatment.

4.7 Step 7: Monitor Across Scales

Although monitoring requires a considerable investment of time and resources, it is a valuable undertaking that provides key information for effective restoration actions via the process of adaptive management (Aplet et al. 2014). Only by measuring the outcomes of restoration treatments can managers evaluate whether the desired results were achieved, whether unexpected negative effects occurred, or whether additional work is needed to complete or refine the management actions to meet the original objectives. Recently, national restoration programs have mandated monitoring as part of the requirement for continued funding (e.g., the Collaborative Forest Landscape Restoration Program; see Briggs et al. [2017]; Davis et al. [2016]; Schultz et al. [2012]).

For each management objective, monitoring metrics or variables should be identified that can be measured both pretreatment and posttreatment in the same locations using the same methods. Pretreatment data should be collected and assessed for all variables of interest as the first step in the treatment planning and prescription development process. Pretreatment data answer the critical question, **"What are the current conditions?"** For many variables—specifically those that change over time with seasons, weather, and climate—measurements should be made on areas to be treated and adjacent untreated areas that will serve as controls for comparison of treatment effects over time and space.

After treatments are completed, the first question to address through monitoring is, **"Were the treatments implemented as planned?"** In other words, was the prescription followed as expected to achieve the planned change in variables such as basal area, tree density, spatial heterogeneity, species composition, and retention and distribution of elements such as snags and downed wood? This phase or type of monitoring is known as “implementation monitoring” and is often done either during or shortly after treatment work is finished on the ground (Hutto and Belote 2013). Data collection is often the responsibility of the project administrator, who compares what was removed to the pretreatment data and to the prescription. If problems or errors are identified during this phase, project administrators will need to work with the entity completing the work to correct them as soon as possible. If this is not feasible, the lessons learned may be used to improve the implementation of future prescriptions. As part of implementation monitoring, changes made by the treatments may also be assessed at broader spatial scales in both the short term and longer term. Evaluation would include a much larger landscape than individual treatment units or stands (e.g., the mixture of openings or meadows of different sizes and patches of forest of different densities and sizes) and might be possible to assess only through analysis of aerial imagery before and after treatment, or via other remote sensing monitoring methods.

The second question to address through monitoring is, **“Did the treatments lead to progress toward the desired outcomes?”** This is known as “effectiveness monitoring” and is intended to evaluate the effectiveness of the treatment in meeting the stated management objectives necessary to achieve the desired conditions (Hutto and Belote 2013). For this type of monitoring, the scale and type of desired condition will determine the most effective survey or sampling design. For example, understory composition and cover should be measured using enough plots or transects distributed in a way that allows the field crew and project manager to identify any important changes at relevant spatial scales and timeframes. A significant increase in invasive plants would be important to identify within a stand, but probably would not be detected if sampling were done too soon after treatment or at too few locations in a stand. In contrast, measurements of change in wildlife populations or habitat use might be important to make soon after treatment as well as over much longer timeframes, and the spatial scale relevant to detecting and monitoring wildlife would also vary widely depending on the ecology and behavior of the species or guilds of interest.

When monitoring data are evaluated, an important additional question to ask is, **“Did the monitoring methods effectively measure the variables we were interested in: the variables that represent the desired conditions?”** Sometimes, no change is detected through monitoring not because no change occurred, but because either the method used or the scale at which it was applied was not effective in detecting an actual change in that variable. For example, surface fuels are commonly measured using Brown’s transects (Brown et al. 1982), but if fuels are measured along only one 50-foot Brown’s transect at each of 10 points in a 300-acre stand, the number and distribution of those transects are not likely to fully or accurately sample the actual fuels present throughout the stand. Those 10 relatively short transects would probably by chance often miss areas where fuels had accumulated either naturally or because of the treatments. If there is a threshold of concern about fuels (or invasive plants, or any other variable) that would trigger a certain management need or action if detected, care should be taken to ensure the monitoring methods would be able to detect that level of change.

Monitoring methods should be reviewed each season and modified or altered as needed for future seasons to improve the data collection process and the relevance of the information gathered. At the same time, only data collected with the same methods between time periods should be compared. Ideally, monitoring methods will be based on power analyses or other assessments that are conducted before monitoring begins, to identify the most effective monitoring approach (scale, replication, and sampling techniques) for the variables of interest in the areas to be treated. However, monitoring methods need not be extremely complex or expensive to be effective. If progress toward desired conditions and thresholds of concern in the key variables for a given project can be evaluated at relevant scales using a method such as repeat photography, the project staff and stakeholders may decide that this approach is effective for their objectives.

If the project staff and stakeholders evaluate the pretreatment and posttreatment data and determine that the answer to all three of the monitoring questions is "yes" for the variables and desired conditions of interest, they can be reasonably confident that all elements of the project are working well. If, however, the answer to any of these three questions is "no," the relevant part of the process—prescription, implementation, progress toward desired conditions, monitoring methods, and data evaluation—should be changed or adapted so that either the outcome of this project or the outcomes of future projects can be improved over time. Steps to help ensure success and accountability of all staff and stakeholders in this endeavor include: preparing a written monitoring plan that addresses the questions and considerations described earlier; allocating sufficient staff time and resources to data management and analyses as well as data collection in the field; and scheduling regular presentations and evaluations of monitoring data after each field season that will contribute directly to the adaptive management cycle. As stated by Aplet et al. (2014: p. 5), "Monitoring should be designed to answer the fundamental question: Are treatments achieving desired effects without causing anticipated negative effects?"

Effective monitoring relies on clearly stated monitoring objectives and the identification of metrics that can be used to assess progress in achieving goals and desired conditions. Metrics represent key attributes of landscape and stand structure that can be efficiently measured to provide information about forest structure, composition, and function. The Front Range Roundtable, through the Collaborative Forest Landscape Restoration Program, has defined a series of metrics for monitoring Front Range forest restoration projects at landscape and stand scales (Briggs et al. 2017; Clement and Brown 2011; Dickinson and Giles 2014; Pelz and Dickinson 2014). Although these metrics (and their methods of measurement) are continuing to evolve, they provide a useful reference for planners and managers on the Front Range.

4.7.1 Landscape-Scale Monitoring

At the landscape scale, metrics are concerned with vegetation pattern and its influence on landscape-level ecological processes such as fire behavior and watershed function. Landscape metrics monitored by the Front Range Roundtable include (1) landscape spatial heterogeneity, (2) landscape fire behavior, (3) watershed function, and (4) wildlife.

Landscape spatial heterogeneity—Landscape spatial heterogeneity is the spatial pattern and juxtaposition of vegetation patches and other landscape features. Dickinson and Giles (2014) and Dickinson et al. (2016) describe techniques for characterizing and monitoring changes in landscape spatial heterogeneity using aerial imagery and the FRAGSTATS program (McGarigal et al. 2012). Example canopy cover metrics include patch area/size (PA), area of each patch type as a percentage of total landscape area

(PLAND), and percentage of total landscape area represented by the largest patch (LPI). Desired trends in these metrics with restoration treatments are described in Dickinson et al. (2016).

Landscape fire behavior—Landscape vegetation patterns can be tied to landscape fire behavior through spatial fire models such as FlamMap (Finney 2006). Restoration treatments can be modeled by changing base inputs (canopy cover, canopy base height, canopy total height, canopy bulk density, and surface fuel model) to depict posttreatment conditions. These methods are described in detail in Vaillant et al. (2013), with an example application provided in Ager et al. (2014). Ideally, monitoring data from stand-level measures (see following) are used to modify inputs to the model. Predicted changes in landscape fire behavior (including crown fire activity, flame lengths, fireline intensity, rates of spread, and spotting distances) due to treatments can then be evaluated.

Watershed function—Watershed function represents the capture, storage, and release of water within a watershed with subsequent effects on the transport and distribution of materials such as soil and woody debris within the watershed. Restoration treatments are intended to maintain watershed function within a natural range of variability necessary to support important terrestrial and aquatic habitats, species, and ecosystem services, with emphasis on preventing excessive soil loss, debris flow, and deposition after wildfire events. Metrics to assess watershed function based on the Forest Service's Watershed Condition Framework (USDA Forest Service 2011a,b) are currently being incorporated into monitoring of Front Range forest restoration projects through the Collaborative Forest Landscape Restoration Program. The Watershed Condition Framework covers a wide range of physical and biological processes in both aquatic and terrestrial systems that, when combined, provide an overall assessment and rating of watershed condition from good to fair to poor. Specific indicators of watershed condition include such attributes as water quality, aquatic habitat and biota, and riparian vegetation.

Wildlife—Restoration efforts may be aimed at enhancing and increasing wildlife habitats that are currently rare on the landscape and that, if restored, will benefit those species that may also be rare due to lack of habitat. However, wildlife populations are often affected by other abiotic and biotic factors in addition to treatments (e.g., weather, climate, food web interactions). Some species will increase in population size following forest restoration treatments, whereas others may not; for many species, the change that is measured will depend on the spatial and temporal scale of both the treatments and the monitoring efforts. On the Front Range, a team of wildlife specialists affiliated with the Front Range Roundtable determined a suite of species to monitor during Collaborative Forest Landscape Restoration Program efforts based on several factors: the degree to which the occupancy and density of those species reflect the condition of the ecosystem; the key ecological functions of the species (Marcot and Vander Heyden 2001); the political mandate to monitor species listed as threatened, endangered, or sensitive by Federal or State agencies; socioeconomic considerations (game species, watchable wildlife); and the existence of protocols previously tested and found effective. Species selected were the golden-crowned kinglet (*Regulus satrapa*), olive-sided flycatcher (*Contopus cooperi*), pygmy nuthatch (*Sitta pygmaea*), mountain bluebird (*Sialia currucoides*), Williamson's sapsucker (*Sphyrapicus thyroideus*), hairy woodpecker (*Picoides villosus*), northern goshawk, pine squirrel (*Tamiasciurus hudsonicus*), and Abert's squirrel. The occupancy and density of most of these species at treated and untreated sites throughout the Collaborative Forest Landscape Restoration Program landscape is being measured via Integrated Monitoring of Bird Conservation Regions protocols by the Bird Conservancy of the Rockies in alternate years over 10 years (Hanni et al. 2016; White et al. 2015). Additional species-specific monitoring efforts are in progress for the northern goshawk and Abert's squirrel (Casey Cooley, Colorado Parks and Wildlife, oral communication, 2017).

4.7.2 Stand-Scale Monitoring

At the stand scale, monitoring uses a plot-based sampling approach (fig. 31) that collects information on key attributes of stand structure and composition, including (1) tree density, (2) species composition, (3) tree size distribution, (4) tree age distribution, (5) spatial heterogeneity, (6) surface fuel loads, (7) fire behavior, and (8) understory vegetation.

Tree density—Tree density is the number of trees per ground area, typically expressed as trees per acre as well as by basal area. Restoration treatments are intended to reduce tree density. Plot-based monitoring can measure tree density within fixed-area plots (simply as the count of trees within the plot), or in variable-radius plots using a basal area prism.

Species composition—Species composition represents the relative proportion of different tree species within a stand. Treatments are generally intended to increase the ratio of ponderosa pine to other conifer species, such as Douglas-fir. Species names should be recorded for trees that are tallied as part of the density sample in order to arrive at species composition.

Tree size distribution—Stands that have been fire excluded often exhibit a steep reverse-J size-class distribution, representing an overabundance of smaller-diameter trees (e.g., less than 4 inches). The change in size-class distribution can be assessed before and after treatment to determine whether treatments are reducing the proportion of smaller-diameter trees in the stand relative to larger-diameter trees. The stand-quadratic mean

Figure 31—Monitoring crew collecting surface fuels data using a plot-based monitoring approach (photo: R. Addington, The Nature Conservancy, used with permission).

diameter can be used as a metric here as well, with treatments intended to increase stand-quadratic mean diameter. Tree size distributions by size classes can be constructed if tree diameters are measured as part of the density sample.

Tree age distribution—Similarly, tree age distributions can be constructed if trees in the density sample are cored and aged. Measurement of tree age is one of the more difficult and time-consuming components of monitoring, however, so it may be confined to a subset of plots. Old trees (>150 years old) can also be qualitatively assessed based on morphological characteristics (Huckaby et al. 2003a). Restoration treatments aim to increase the ratio of old to young trees through removal of young trees and retention of old trees.

Spatial heterogeneity—Spatial heterogeneity is the spatial distribution of trees within the stand, often characterized by tree groups, scattered individual trees, and openings. Restoration treatments are intended to create non-uniform stand structures by enhancing existing tree groups and creating openings. Methods for characterizing spatial heterogeneity at the stand scale are described by Pelz and Dickinson (2014), with spatial metrics similar to those referenced earlier for landscape heterogeneity. Plot- or transect-based approaches can be used here as well (Briggs et al. 2017), whereby openings, tree groups, and single individual trees are characterized according to relative proportion and spatial patterns.

Surface fuel loads—Surface fuel load is the amount of woody material on the forest floor, typically characterized by size class (1-, 10-, 100-, and 1000-hour fuels) as well as litter and duff depths. The goal of restoration treatments is to reduce surface fuel loads over time, though an increase may be expected immediately after treatment as fuels are redistributed from the tree canopy to the forest floor. A modest amount of downed wood (usually 1000-hour fuels) is also desirable, as it provides cover for wildlife. Surface fuels can be characterized using Brown's transects (Brown et al. 1982) or the photoload technique (Battaglia et al. 2005; Keane and Dickinson 2007a, 2007b).

Fire behavior—Surface fuels and other stand attributes can be linked to fire behavior models to predict changes in fire behavior due to treatment. Fire behavior metrics may include flame lengths, rates of spread, fireline intensity, and crowning index. Modeling systems such as the Fire and Fuels Extension of the Forest Vegetation Simulator (Rebain 2010; Reinhardt and Crookston 2003), the Fuels Characteristic Classification System (Prichard et al. 2013), and Feat-Firemon Integrated (Lutes et al. 2009) are all useful tools for this purpose.

Understory vegetation—"Understory vegetation" describes the amount and types of plants below the forest canopy. Primary vegetation functional groups are graminoids, forbs, and shrubs. Increases in native understory vegetation cover and diversity are expected with restoration treatments. Minimizing exotic plant invasions is also an objective. Understory vegetation cover by functional groups or species can be measured along transects using quadrat, point-intercept, or line-intercept approaches.

Numerous approaches and sampling methods have been developed for plot-based monitoring. Elzinga et al. (2001) provide an overview of the strengths and weaknesses of various approaches. They also discuss principles of monitoring plan development and sample design, including components such as plot distributions and sample-size analysis to determine how many plots are necessary to meet monitoring objectives. We encourage readers to refer to Elzinga et al. (2001) for a more in-depth discussion of monitoring approaches in general, and to Davis et al. (2016) for recommendations for multiparty monitoring under the Collaborative Forest Landscape Restoration Program. For the Front Range Collaborative Forest Landscape Restoration Program, Clement and Brown (2011) describe monitoring approaches based on Common Stand Exam protocols implemented by the U.S. Forest Service. Additional resources specific to the Front Range include monitoring protocols developed by the Colorado Forest Restoration Institute (Wolk and Hoffman 2016; Wolk et al. 2015), and methods described by Briggs et al. (2017).

We also encourage the use of remote sensing-based approaches to monitoring: aerial photography, satellite imagery, or light detection and ranging (LiDAR; Hall et al. 2005). Remote sensing provides a viable option for monitoring and should be implemented in tandem with plot-based monitoring to the extent practicable. Pelz and Dickinson (2014) describe one such approach to monitoring spatial heterogeneity based on aerial imagery that is being implemented for Collaborative Forest Landscape Restoration Program projects by the Front Range Roundtable.

5. Additional Considerations for Front Range Forest Restoration

5.1 Adopting an Interdisciplinary Team Approach

In practice, only rarely would any one individual or entity be expected to follow from beginning to end the restoration process described in section 4. It is more likely the process will be divided among several individuals or entities who take on discrete tasks. For example, planners may start at the broad landscape scale and, through a series of assessments, identify priority treatment areas, which are then handed over to project silviculturists to develop treatment plans and prescriptions and oversee implementation of the treatment. Other groups may become involved later in the process, such as during the monitoring phase. Overall, the restoration process may be undertaken through an interdisciplinary team approach to make the process more manageable and to capture input from a range of disciplines and expertise.

5.2 Compartmentalizing the Problem

As with any complex problem, we encourage planners and managers to compartmentalize the larger restoration problem into smaller, more manageable parts. The restoration process we have outlined is intended to help compartmentalize the restoration process by offering smaller, more manageable components across scales. Front Range forest restoration can also be physically compartmentalized according to defined geographic boundaries such as (1) northern versus southern Front Range, (2) fourth-level watersheds, (3) wildland-urban interface, and (4) physiographic settings.

Northern versus southern Front Range—A first step may be to distinguish between the northern and southern Front Range, and to consider key climatic and geological differences between these geographies and their implications for disturbance regimes and forest developmental process (see panel 3). For example, a key distinction between the northern and southern Front Range is summer precipitation, with the northern Front Range on average receiving less summer precipitation due to a weaker monsoonal flow pattern. Planners and practitioners working on the northern Front Range may therefore want to consider treatments that emphasize heavier reductions in density compared to the southern Front Range to increase resilience to drought.

Fourth-level watersheds—Within both the northern and southern Front Range, 4^{th} level (HUC-8) watersheds provide a useful organizational unit for broad landscape evaluations, as many of the ecological processes such as fire that we hope to influence through restoration are relevant at this scale. Furthermore, with the emphasis on forest management for the protection of water resources in the Front Range, a watershed-based approach is particularly relevant. The organization of watersheds by scale (e.g., from 4^{th} level watersheds to 6^{th} level, HUC-12 watersheds) also allows a nested approach to planning across scales. This approach is analogous to the discussion of scale in section 3.2, whereby planning can begin at the HUC-8 level and work toward identifying priority subwatersheds at the HUC-12 level. There are seven HUC-8 level watersheds covering

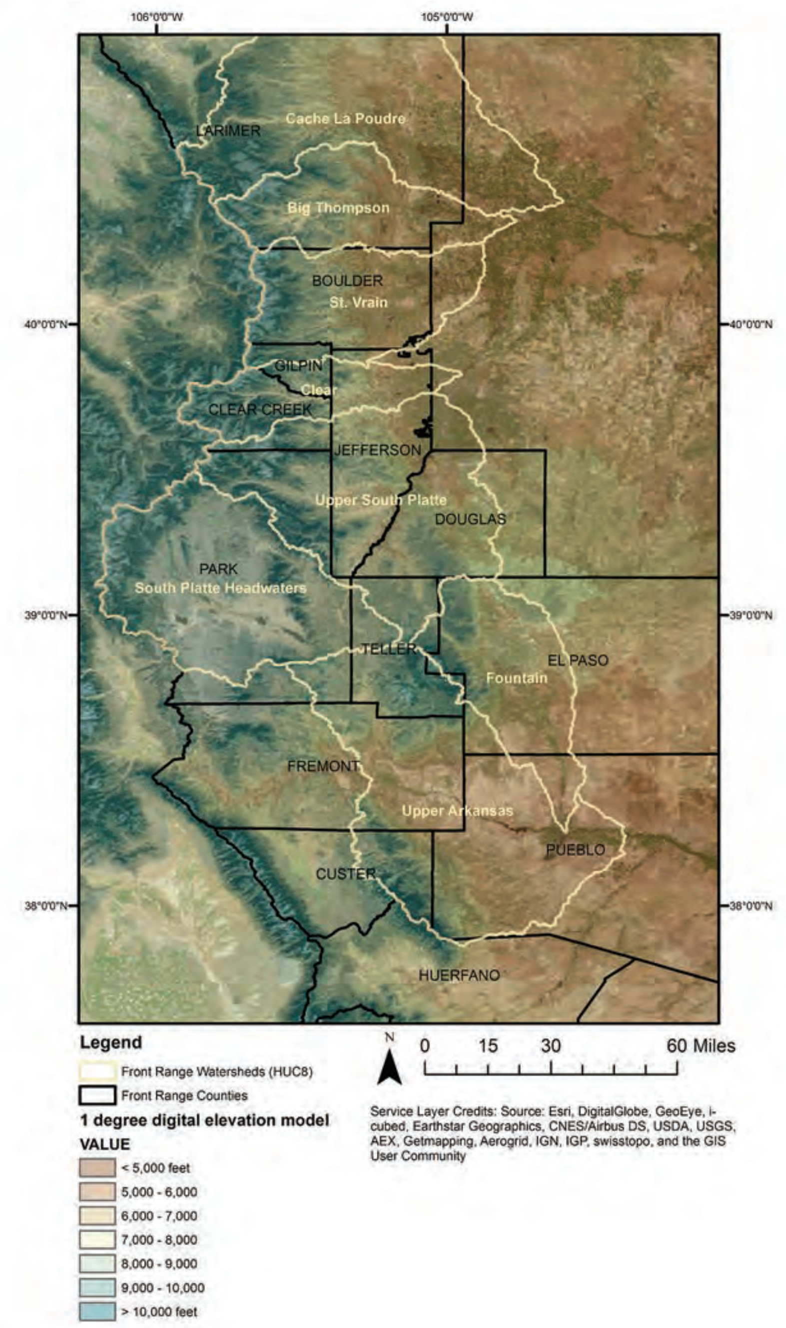

Figure 32—Fourth-level (HUC-8) watersheds of the Front Range and alignment with county boundaries.

about 5.5 million acres across nine counties on the Front Range (fig. 32). From north to south, these watersheds are the Cache la Poudre (~1.2 million acres) and Big Thompson (~532,000 acres) watersheds in Larimer County; the Saint Vrain watershed (~626,000 acres) in Boulder County; Clear Creek watershed (~364,000 acres) in Jefferson, Gilpin, and Clear Creek Counties; the South Platte Headwaters watershed (~1.0 million acres) in Park and Teller Counties; the Upper South Platte watershed (~1.1 million acres) in Douglas, Jefferson, Teller, and Park Counties; and the Fountain Creek watershed (~593,000) in Teller, Douglas, and El Paso Counties. Each of these watersheds is bounded to the west by the Continental Divide. Several of the watersheds also align with county boundaries in what might be thought of as "geopolitical" organizational units that combine physical features of the watersheds with social and political factors attributed to individual counties. For example, counties may differ widely in their land use designations, zoning, and the degree to which development within the wildland-urban interface has occurred. Counties may also differ in the extent to which Community Wildfire Protection Plans have been developed and implemented.

Wildland-urban interface—The degree of wildland-urban interface development represents another way in which the Front Range can be compartmentalized. Distinguishing between wildland-urban interface areas versus non-wildland-urban interface areas can help in determining where restoration is a feasible management goal versus (or in addition to) fuels reduction aimed primarily at protecting communities, homes, and infrastructure. The wildland-urban interface can be mapped across the Front Range using housing density data obtained through the Colorado State Forest Service's Colorado Wildfire Risk Assessment Portal (CO-WRAP), as well as through the Colorado Forest Restoration Institute at Colorado State University, which maintains a database of locations for all buildings on the Front Range over 1,000 square feet in size (Caggiano et al. 2016).

Physiographic settings—Each of the HUC-8 watersheds on the Front Range is unique in its physiography, topography, and the way in which disturbance histories and forest developmental processes have created patterns in forest structure and composition over time. Further compartmentalizing HUC-8 watersheds by physiographic settings can be a useful way of describing expectations for variation in forest structure. Physiographic settings may include lower versus upper montane and dry sites versus wet sites (as in section 3.7), and may follow more of a gradient-based description according to the dominant environmental gradients described in section 3.4. At a treatment scale, features such as ridges, mid-slopes, and bottoms may provide useful physiographic settings around which to understand and describe variability in forest structure to inform restoration work through the development of prescriptions tailored to individual settings.

5.3 Garnering Support Through Collaboration

Restoration projects can affect adjacent landowners, influence how people use and value their local forests, substantially alter the forest ecosystem, and require substantial financial resources. Some individuals and organizations may support restoration and wish to contribute to the success of the project. Others may be skeptical of forest restoration; on-the-ground activities, such as mechanical harvesting and prescribed fire, can be emotionally and politically charged and result in opposition by local residents and interest groups.

It is beneficial for managers to work with individuals and organizations interested in, and affected by, restoration to develop a collaborative process. Collaboration can lead to broad social and political support, help to avoid future conflicts, and bring technical and financial resources to projects (Kaufmann et al. 2009; Seidl et al. 2016; Sturtevant et al. 2005). Collaboration is particularly important in planning for climate change, as climate-related impacts are cross-boundary and best addressed by multiple parties (scientists, managers, and stakeholders) to ensure that management strategies are science based, practical, and socially acceptable (Peterson et al. 2011; Swanston and Janowiak 2016). In general, collaboration in forest restoration involves a commitment by individuals and organizations to foster common knowledge about forest conditions and restoration opportunities, define clear goals and objectives, develop ideas for restoration approaches, and promote adaptive management through monitoring and learning.

Collaboration can range from informal, ad hoc interactions and communications to formal, structured processes. Similarly, investments in collaboration can vary with approach. The choice of collaborative approach depends on:

- The number and diversity of interested and affected individuals and organizations;
- Each party's expectations of the collaborative process and outcomes;
- Each party's capacity to regularly participate and substantively contribute;
- The project phases and elements that can or cannot incorporate collaborative processes (based on applicable laws and regulations);
- The degree of complexity and potential for conflict (e.g., project areas that are very large, are adjacent to communities, or encompass sensitive or protected species; proposed use of prescribed fire; past conflicts over forest management activities);
- The degree of trust in forest managers; and
- Available human, financial, and time resources to carry out a collaborative process.

An initial step in choosing the appropriate collaborative approach is to engage all parties in project-scoping to assess these elements. Setting clear expectations about what the process is and is not intended to achieve, and assembling the resources needed to meet these expectations, can make collaboration effective and efficient (Burns and Cheng 2007).

Key to effective collaboration is to structure collaborative activities with the outcome in mind. The contents of this report (particularly section 4) can be used to frame the purpose and outcomes of collaborative activities. The following are potential collaborative opportunities to consider.

Assessing forest conditions and restoration needs—Gathering baseline information and evaluating existing conditions to determine if and where restoration is warranted can be a productive initial collaboration phase, as it provides an opportunity for all parties to provide information and perspectives on forest conditions, learn from one another, and generate shared knowledge about the landscape. Some collaborative groups involved in forest restoration across the western United States have gone so far as to have participants collect information on historical forest structure and fire regimes during the assessment phase. Involving all parties in the assessment phase may help to build support for management actions and avoid future conflict. Field trips, literature reviews of scientific studies and technical reports, and subject-matter expert presentations provide valuable forums for fostering learning and deliberation within collaborative groups.

Identifying restoration opportunities, goals, and approaches for landscapes and treatment units—Collaboration participants can jointly prioritize where restoration actions would have the greatest impact relative to the values within the landscape of interest. Romme et al. (2012) offer a framework that can help to guide collaborative decisionmaking in the context of historical range of variability and social acceptability. The information presented in section 4 can also help to frame collaborative dialogue about restoration needs and opportunities, desired conditions, project goals, and approaches across scales. For example, locating restoration treatments next to existing openings or past fires can expand the geographic area where fire can be managed safely and provide an ecological benefit. Participatory mapping is a technique that involves all parties examining geospatial data about the landscape as a way to spatially locate restoration needs and opportunities. Participants may also have the opportunity to mark stands to generate ideas and understanding about restoration prescriptions.

Coordinating implementation of restoration projects—In some instances, restoration may involve adjacent landowners carrying out management activities. Coordinating treatment areas and prescriptions can expand the ecological impact of restoration, create efficiencies for operators, and provide more attractive economic opportunities for wood product end-users. Additionally, other governmental and nongovernmental organizations involved in watershed protection, wildlife, and recreation may be able to provide financial resources to address their interests.

Creating and implementing an adaptive management strategy—Concerns over the uncertainty of restoration impacts to the ecosystem, economic costs and benefits, and social values can be addressed through a collaborative adaptive management strategy. Participants can identify observable objectives, indicators, and techniques to measure or observe indicators, and help carry out monitoring. Objectives and indicators may be qualitative or quantitative. A rule of thumb is to focus on a small number of indicators, but measure them consistently, reliably, and thoroughly. The key consideration is that all parties commit time, energy, and resources to adaptive management.

Collaboration is not required for successful restoration (and can slow the restoration process in some cases) but is a useful way of building a common understanding and support for restoration, and expanding ecological, economic, and social benefits. Collaboration does require all participants to commit to and invest in the process. Setting clear expectations about the process, desired outcomes, and available resources to carry out collaboration is necessary.

5.4 Developing Long-Term Maintenance Plans and Special Designation for Treatment Areas

Restoration is not a one-time event but rather a process that involves a long-term program of work to affect forest vegetation structure and, in some places, reinitiate ecological processes, especially fire. The time, energy, and financial resources dedicated to a forest restoration project can be substantial. Without maintenance over time, the benefits of treatment will eventually be lost (Stephens et al. 2012a). Broadcast prescribed fire is the preferred means of maintaining treatments for maintenance of important ecological processes and continued enhancement of the structural diversity initially achieved by mechanical treatments. But the degree to which prescribed fire can be used to maintain treatments will vary on the Front Range depending on proximity of treatment areas to the wildland-urban interface and other factors that limit the use of prescribed fire, such as smoke management. However, we encourage the use of prescribed fire as a maintenance treatment when and where possible.

In addition to maintaining restoration treatments, we recommend that future forest management activities within restoration project areas be designed and implemented following the spirit and intent under which restoration projects were started. The use of special designations in forest plans may help to sustain restoration projects by recognizing where restoration has been achieved and ensuring its ecological integrity over time.

5.5 Informing Forest Plan Revision

The 2012 Forest Service planning rule codified the importance of ecological restoration as the overarching guiding principle for the management of National Forest System lands (USDA Forest Service 2012). Therefore, the principles of restoration outlined here can also be used to inform revision of forest plans along the Front Range, which are scheduled to occur in the next several years. This will ensure that restoration goals and approaches are congruent with forest plans. In turn, analysis and implementation of forest management projects are facilitated, as projects are required to show how their "purpose and need" is derived from the forest plan.

The principles outlined in this document can inform several different components of the forest planning process and implementation, including:

- **Forest assessments—**This document can help to frame assessments by identifying the most important elements or features of Front Range lower montane forests across spatial scales. The assessments done for forest planning can then become a valuable resource for treatment prioritization.
- **Plan components—**The principles outlined here can help with defining desired conditions and management objectives for dry, frequent-fire forests on the Front Range. This document highlights key considerations that might be translated to standards or guidelines for forest management and identifies key attributes that can translate to indicators for analysis of effects.
- **Monitoring—**Monitoring is a required component of plan implementation. Monitoring metrics described in section 4 may be incorporated within forest plans; metrics for socioeconomic monitoring may also be added.

Because forest restoration activities also occur on non-Federal lands near national forests, it is important to ask non-Federal managers and landowners to compile information about past and planned treatments to integrate into forest assessments, plan components, and monitoring.

6. Information Needs

Continual learning is an essential part of the adaptive management process. We identified information needs through the development of this document. Following are some key information gaps that should be addressed to continue to advance restoration on the Front Range.

6.1 Effects of Restoration Treatments on Fire Behavior

Restoration treatments are expected to reduce undesirable outcomes associated with fire, including large patches of complete tree mortality, damage to homes or infrastructure, water-quality decline, and postfire flooding and erosion. Although much research has focused on evaluating the effectiveness of fuels reduction and forest restoration treatments for other parts of the western United States (Cochrane et al. 2012; Pollett and Omi 2002), the degree to which restoration treatments influence landscape fire behavior is not well known for the Front Range. Martinson et al. (2003) evaluated the influence of treatments within the Hayman Fire on fire spread and burn severity and concluded that large treatments such as the Polhemus prescribed burn (approximately 8,000 acres) and previous wildfires were effective in changing fire behavior, but found variable effects for other treatments. Using a physics-based fire model, Ziegler et al. (2017) found that mechanical restoration treatments were effective in reducing simulated rates of fire spread, fireline intensity, and canopy fuel consumption. In contrast, fuels treatments that were conducted within the Fourmile Canyon Fire apparently did not moderate fire behavior, and instead may have exacerbated it (e.g., increased rates of fire spread and postfire burn severity), possibly due to the large amounts of surface fuels and brush piles that were still present after the treatments (Gartner 2015; Graham et al. 2012). A better understanding of how different treatment types perform during wildfire is needed. As wildfires continue to occur on the Front Range, research should be poised to evaluate the effectiveness of treatments in influencing fire behavior and effects at both landscape and stand scales.

6.2 Effects of Climate Change

Developing appropriate management actions in the face of climate change represents one of the greatest challenges and uncertainties for Front Range forest restoration. What can managers do on the ground to increase resilience and increase the likelihood that forest values will persist under future climate and disturbance regimes? We point out general implications of climate change for Front Range forests in section 3.9, but much more information is needed. More detailed climate change strategies should be developed for the Front Range through collaborative processes that incorporate tools such as species vulnerability assessments, scenario planning, and climate envelope modeling. Fire behavior modeling can also be useful at a treatment scale to evaluate the types of forest structures that may (or may not) hold up under the more extreme weather and fire conditions expected with climate change. Sherriff et al. (2014), for example, used 99th-percentile weather and fuel moisture conditions in their fire behavior modeling to represent the extreme conditions under which we expect future fires to occur. Treatments probably will need to be more extreme (i.e., higher basal area reductions and lower residual stand densities) to withstand extreme events. Collaboration and public outreach become that much more important in this context to gain acceptance of such treatments.

6.3 Range of Variation in Historical (or Reference) Fine-Scale Structure and Spatial Heterogeneity

Research along the Front Range has provided us with valuable information about historical fire regimes and patterns of landscape forest structure (e.g., Fornwalt et al. 2002; Huckaby et al. 2001; Kaufmann et al. 2000; Schoennagel et al. 2011; Sherriff and Veblen 2006; Veblen and Donnegan 2005). Less is known, however, about historical patterns of fine-scale (<1 acre) structure and spatial heterogeneity. Research conducted over a broad geographic range is needed to more fully capture the variation that occurs throughout the Front Range, especially along gradients in elevation, slope, aspect, and latitude. This information is needed for the development of local ecological models as described in section 3.7. The Front Range Forest Reconstruction Network (FRFRNet) is a research project begun in 2012 to provide historical stand structure information, including fine-scale patterns of structure and spatial heterogeneity. The information generated by this research will help to guide the development of more detailed desired conditions for stand structure, such as more specific ranges for basal area, tree density, proportions of trees in groups, age-class and size-class distributions, and species compositions for given physiographic settings (see Brown et al. 2015).

6.4 Patch Sizes of High-Severity Fire

Although much research has been conducted to evaluate historical fire regimes, there are still unknowns and ongoing debate about patch sizes of historical high-severity fire in dry forest types of the Front Range (e.g., Fulé et al. 2014; Williams and Baker 2014). This document recognizes the important historical role of high-severity fire in shaping Front Range forests and emphasizes that restoration is not intended to remove high-severity fire from the landscape (nor could it, realistically). Yet a better understanding of maximum acceptable patch size based on values at risk within the wildland-urban interface and the potential for negative impacts to ecosystem services such as water provisioning is needed.

6.5 Effects of Restoration Treatments on Ecosystem Services Provisioning and Wildlife

In section 3.8 we discuss the importance of identifying the ecological processes, functions, and ecosystem services that restoration treatments are intended to protect or enhance. Additionally, in section 4 we describe the importance of prioritizing treatment locations and designing treatments to meet objectives associated with ecological values in individual landscapes. Through monitoring and research, it is important to determine whether treatment objectives are being met and whether restoration treatments are having the intended impact on ecological values. For water resource provisioning, for example, more information is needed through modeling and observations (especially where fire interacts with treatments) to determine whether treatments are having the intended outcome of protecting water resources from postfire soil erosion and sedimentation. Similarly, more information about key habitat components and characteristics for focal wildlife species is needed to better plan and implement treatments for wildlife benefit, and to better anticipate the response of individual species to restoration treatments. This is particularly important for species identified as Species of Greatest Conservation Need by Colorado's 2015 State Wildlife Action Plan (Colorado Parks and Wildlife 2015), including Preble's meadow jumping mouse (*Zapus hudsonius preblei*), Mexican spotted owl, Abert's squirrel, and lynx (*Lynx canadensis*). This information should include habitat features at the stand scale (e.g., tree groups, snags, downed wood) as well as the landscape scale (e.g., habitat connectivity and configuration).

6.6 Treatment of Residual Biomass

Mechanical treatments generate residual material such as tree boles and slash. Often called activity fuels (because they result from the treatment activity itself), these residual fuels can be challenging to deal with during and after the primary treatment activity. Several methods are currently in use on the Front Range for dealing with residual material, including piling and burning, lop-and-scatter, and mastication or chipping. Whole-tree removal is also an option in some cases, although it can be costlier to implement than other methods. More information about the economic and ecological costs and benefits associated with these different treatment methods for residual biomass is needed. Additionally, guidelines to assist managers in determining when and where different methods are most appropriate would be useful.

6.7 Postburn Landscape Management

Much of the Front Range land area has already experienced broad-scale, high-severity wildfire, and ways to best manage these postburn landscapes into the future need to be identified. In many cases, variable fire effects have created desirable patterns in landscape and stand structure within burn perimeters. Managing these areas to maintain and enhance desirable ecological features into the future is an important aspect of the overall landscape restoration program of the Front Range (Seidl et al. 2016). These areas provide opportunity to anchor and expand into larger networks of restored forests. Opportunities for broadcast prescribed fire may also exist within interior areas of burn perimeters, as these areas may have lower fuel loads than other parts of the Front Range.

6.8 Longevity of Restoration Treatments

Forests are dynamic; trees grow, new trees establish, and surface fuels accumulate faster than they decompose on the Front Range. An understanding of these processes across productivity gradients and various management activities is essential for planning maintenance treatments and intervals. Empirical data for tree growth, tree establishment, and surface fuel accumulation are limited for ponderosa pine and dry mixed-conifer forests of the Front Range. This is especially true for forests that are being managed for spatial complexity, which creates variability in resource availability that will affect these processes.

6.9 Novel Ecosystems

With changes in climate, natural disturbance regimes, and species geographic distributions, the potential for novel ecosystem development is high. Novel ecosystems may include novel species assemblages and structures that have no historical analogue from which we can draw information (Seastedt et al. 2008). Novel ecosystems may still provide valuable ecosystem services, however, and efforts should be made to understand ecosystem function in these systems and to explore their social acceptability (Seidl et al. 2016).

6.10 Information Databases

There is a general need for more spatially explicit inventories and databases throughout the Front Range that can be used for landscape planning, treatment prioritization, and treatment design. Detailed inventories of old-growth stands, reference stands, and critical wildlife habitats are all especially needed. Desired future "knowledge bases" should also be developed. We should not be limited in our approach to restoration by the information currently available, but rather should think ahead to the information we may need in the future to develop sound restoration strategies. A proactive approach to restoration is particularly important in the context of climate change.

7. Conclusions

The intent of this document is to provide a guiding framework for incorporating ecological dynamics into the planning and implementation of restoration projects across scales, and to address key information gaps surrounding restoration of ponderosa pine and dry mixed-conifer forests on the Front Range. Beyond this original intent, we hope that this document will serve as a basis for continued dialogue about forest management and restoration on the Front Range, and what we as scientists and managers can do to promote long-term forest resilience and the continued delivery of important ecological goods and services. Scientific knowledge and management practices will continue to evolve in the coming years as research and monitoring are conducted and new management practices are evaluated. It is important that new knowledge be continually incorporated into management. This report is meant to be a "living" document. We welcome input and suggestions that may serve as a foundation for future revisions of the document. In the spirit of adaptive management, information guiding restoration such as that provided here should be continually updated and applied as learning occurs through time.

8. Glossary

Adaptive capacity—The general ability of institutions, systems, and individuals to moderate the risks of climate change, or to realize benefits, through changes in their characteristics or behavior. Adaptive capacity can be an inherent property or it could have been developed as a result of previous policy, planning, or design decisions.

Age class—A group of trees that are about the same age (Smith et al. 1997). Contrast with **cohort**.

Basal area—The cross-sectional surface area of the trees in a stand at breast height (4.5 feet, or 1.37 meters above ground), generally expressed per unit of ground area such as square feet per acre or meters squared per acre (Helms 1998).

Biological legacy—Any organism, or organic structure or material, that persists on the landscape following disturbance events such as fire (Helms 1998). Biological legacies may exist at multiple scales and may not be readily apparent. At fine scales, downed wood is an example of a biological legacy; at the landscape scale, forest structure and age class arrangement may be a biological legacy.

Broad-scale—Pertaining to an area relatively large in its spatial extent, defined here as 100,000 to 1,000,000+ acres. Contrast with **fine-scale**.

Day-lighting—Removing vegetation around a tree, group of trees, or other forest structure in order to increase the exposure or available light to that structure.

Clump(y)—See **tree clump**.

Cohort—Trees that established in response to a disturbance or management event under the same general conditions (Smith et al. 1997). A cohort may include one or many age classes. Contrast with **age class**.

Diameter at breast height—The diameter of a tree stem measured at breast height (4.5 feet or 1.37 meters above the ground). The height of the ground is usually measured from the uphill side of the tree base.

Disturbance—Any relatively discrete event in time that disrupts ecosystems and their composition, structure, and function (Barnes et al. 1998). Fire and insect outbreaks are examples of natural disturbances; logging is an example of an anthropogenic disturbance (Puettmann et al. 2008).

Disturbance regime—The timing, frequency, extent, and severity of a recurrent disturbance that is characteristic of a specific area or ecological system (Puettmann et al. 2008).

Downed wood—Dead woody material on the forest floor such as downed logs and limbs.

Ecosystem function—The abiotic and biotic processes that occur in an ecosystem that transfer energy and matter within and between ecosystem components. Examples of ecosystem functions are nutrient cycling, soil development, and water filtering.

Ecosystem process—The physical, chemical, and biological actions or events that link organisms and their environment. Processes include biomass production, decomposition, and nutrient cycling.

Ecosystem service—Any product of the natural environment—such as a commodity (e.g., sawtimber) or function (e.g., water supply, carbon sequestration)—that provides a benefit to people and society.

Environmental gradient—Gradual change of environmental conditions, such as in elevation or moisture availability, that is often reflected by patterns of vegetation structure and composition.

Even-aged stand—Stand in which all trees are from the same age class. Typically, the range of tree ages will be within 20 percent of the rotation age (Helms 1998). Even-aged management systems may temporarily contain more than one age class during a regeneration system, such as following a shelterwood establishment cut. Contrast with **uneven-aged stand**.

Fine-scale—Pertaining to an area relatively small in spatial extent, defined here as an area less than 1 acre. Contrast with **broad scale**.

Fire regime—The characteristic timing, frequency, extent, severity, and seasonality of fires that affect an ecosystem. Fire regimes are typically classified as low-severity or understory, moderate-severity or intermediate, high-severity or stand-replacing, and mixed-severity fire regimes; however, definitions of these terms are not widely accepted. Low-severity or understory fire regimes are typically dominated by frequent surface fires where less than 20 percent of the overstory trees are killed (Agee 1996). High-severity or stand-replacing fire regimes tend to be dominated by infrequent crown fires that kill more than 70 percent of the overstory trees (Agee 1996). Moderate-severity or intermediate fire regimes are moderate between these two extremes (Agee 1996). Mixed-severity fire regimes occur where the severity of fire is variable spatially or temporally, or both, with low-, moderate-, and high-severity fire all present (Perry et al. 2011).

Fire severity—The effect of fire on an ecosystem, usually defined by the degree of soil heating or mortality of vegetation (Keeley 2009). See panel 4 for gradients in fire severity.

Group(y)—See **tree group**.

Historical range of variability—The range of structures, compositions, and processes that characterized ecological systems before Euro-American settlement; often used to inform ecological restoration goals and objectives (Aplet and Keeton 1999; Keane et al. 2009).

Landscape—The features of an area of land (typically on the order of 1,000 to 100,000 acres) that include both its physical and biological elements.

Meadow—Land area covered mostly by herbaceous vegetation with few to no trees.

Montane—Relating to mountains (Helms 1998). Montane ponderosa pine and dry mixed-conifer forests of the Colorado Front Range can be found between approximately 5,500 and 9,300 feet above sea level (Marr 1961; Peet 1981).

Old-growth stands—The (usually) late successional stage of forest development (Helms 1998). In fire-adapted forests of the western United States, this has been further defined as stands demonstrating historical conditions including the forest structure, fire regime, and species composition that characterized these forests before European settlement in the late 1800s (Kaufmann et al. 2007). Note: Individual Front Range ponderosa pines typically begin taking on old-growth morphological traits at around 200 years of age (Huckaby et al. 2003b).

Opening—A nonforested area containing graminoid, forb, and shrub species within a larger forested patch, stand, or landscape. In this document, we distinguish between persistent and transient openings, with persistent openings (e.g., meadows) capable of remaining without trees for long periods of time due to soils, herbaceous vegetation, and surface fire, or due to unsuitable conditions for tree regeneration on dry sites. Transient openings, on the other hand, are areas that once contained trees but lost tree cover due to disturbances such as high-severity fire or insect outbreaks. Transient openings provide sites for tree regeneration and are important for perpetuating variable-aged stand conditions.

Patch—A homogeneous unit distinguishable from the surrounding matrix. Patches can be vegetated or nonvegetated. The definition of a patch will vary with the process and scale of interest. For example, at a stand scale (1–100+ acres), several patches and openings may be distinguishable within a stand, while at a landscape scale the same forested area may appear homogeneously dense.

Prescribed fire—Fire that is intentionally applied to a predetermined area under specified weather and fuel moisture conditions to achieve a management objective. On the Front Range, prescribed fire may include both broadcast burning and pile burning. Broadcast burning is fire applied over a defined spatial extent (e.g., a burn unit), and pile burning is the burning of woody material (branches and small-diameter boles) generated and piled during treatment activities.

Resilience—The ability of an ecosystem to recover its fundamental structures, processes, and functions after disturbances and stresses (Holling 1973; Puettmann et al. 2008).

Resistance—The ability of an ecosystem to absorb disturbances and stresses without altering its fundamental structures, processes, and functions.

Restoration—The process of assisting the recovery of an ecosystem that has been damaged, degraded, or destroyed (SER 2004).

Reverse J—The frequency distribution of tree diameters (diameter at breast height, d.b.h.) often used to represent an uneven-aged stand structure, whereby higher numbers of trees in the smaller diameter classes and fewer trees in the larger diameter classes create a frequency distribution that is shaped like a reverse J.

Safe site—An area protected from fire or other disturbances where tree regeneration may occur. In forests that are adapted to frequent fire, safe sites for regeneration may exist in areas such as rock outcrops or where fine fuels necessary for carrying fire are absent or not continuous. Safe sites may also be the result of localized high-intensity fire related to downed wood and areas of high fuel loadings (Larson and Churchill 2012).

Scale (spatial or temporal)—The geographic extent (spatial scale) or time period (temporal scale) during which a given observation, ecological process, or structure is relevant and meaningful.

Seral stage—A temporary and intermediate stage in a vegetation community that is in the process of succession.

Silvics—The study of how trees grow, reproduce, and respond to their environment.

Silviculture—The art and science of controlling the establishment, growth, composition, health, and quality of forests and woodlands to meet the diverse needs and values of landowners and society on a sustainable basis (Helms 1998).

Silvicultural system—A planned series of treatments for tending, harvesting, and reestablishing a stand (Helms 1998) to meet a defined set of objectives.

Skip—Portion of a stand or treatment unit that is left untreated (Franklin et al. 2013).

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 (Helms 1998). Defined here as 1 to 100+ acres in size.

Stand dynamics—Changes in species composition, forest structure, and function occurring in a stand through time as well as in response to disturbances (Oliver and Larson 1996).

Stand structure—Horizontal and vertical distribution of forest components such as tree species, tree size and age classes, and density (Helms 1998).

Subalpine—Highest mountainous areas that can support forests (Helms 1998). Here we define subalpine forests of the Colorado Front Range as occurring approximately between 9,000 and 11,500 feet above sea level.

Succession—The gradual change in dominance from one group of organisms to another over time (Helms 1998).

Sustainability—Characteristic by which a process or state can be maintained at a certain level indefinitely without loss of the necessary resources to keep the processes going.

Treatment unit—Management unit within which a management treatment may occur, similar to a stand in size (1 to 100+ acres) but defined more by operational boundaries (natural topographic breaks, roads, property boundaries) than by vegetation; may contain multiple forest types or stands.

Tree clump—Two or more trees sharing a common base or touching bases; a multi-stemmed tree (Helms 1998). Contrast with **tree group**.

Tree group—An isolated, generally dense, subset of trees that have interlocking or directly adjacent crowns (Helms 1998; Larson and Churchill 2012), or have the potential to have interlocking or directly adjacent crowns at maturity. Contrast with **tree clump**.

Tree interspace—Areas not currently occupied by trees that occur between tree groups or between individual trees; generally composed of graminoid, forb, and shrub species but may also include areas with rock or exposed mineral soil. Tree interspaces as defined here do not include natural meadows, grasslands, or other semi-permanent nonforested areas. Similar to **opening**, but contrast with **meadow**.

Uneven-aged stand—A stand that is composed of trees of multiple age classes (three or more) consistently through time. Contrast with **even-aged stand**.

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Appendix A—Historical Information Sources for the Front Range

Historical references and data are valuable for current forest restoration efforts by providing us with a sense of historical forest structure and composition. Forest inventory plots established in the early 1900s have been useful for current restoration work in the Southwest (the Woolsey plots) (Huffman et al. 2001; Moore et al. 2004) and the Pacific Northwest (the Munger plots) (Duncan 2004). No such historical inventory plots exist for the Colorado Front Range, but other clues to the historical forest condition are available, including early explorer and settler accounts, early paintings and photographs, and forest descriptions.

Several painters explored the Colorado Front Range in the mid- to late 19th century, including Albert Bierstadt, John Frederick Kensett, and Worthington Whittredge. These painters were associated with the Hudson River School and specialized in landscape paintings. Given the period and dates of many of the paintings, they most likely represent forest conditions before significant disturbances such as logging and grazing associated with settlement. Open stand conditions and tree groups are depicted in several such early paintings (figs. A.1, A.2).

Figure A.1—"Bergen Park," painted by John Frederick Kensett circa 1870. The painting illustrates the open, spatially variable structure of a ponderosa pine stand with an herb-dominated understory. Bergen Park is located near Evergreen, Colorado, about 25 miles west of Denver.

Figure A.2—Painting of Pikes Peak by Albert Bierstadt circa 1860s illustrating single trees, groups of trees, and openings historically characteristic of ponderosa pine stands.

One of the most informative early descriptions of Front Range forests was provided by John Jack (1900), who surveyed and described the Pikes Peak, Plum Creek, and South Platte Timber Reserves in the late 1800s for the U.S. Geological Survey in what is now the Pike National Forest. He wrote:

> *Of all the reserves established by the Federal Government, the three under consideration have probably been the most damaged by fire and been subject to greatest depredations by timber cutters. A comparatively small portion of the total area fails to show traces of forest or surface fires, some of the more recently burned sections presenting a desolate aspect, which under present natural developments is likely to continue for many scores of years. There are a very few thousand acres of merchantable timber where the ax has not been used with evident effect. The best of the remaining timber can not be called large, but it is greedily sought by the lumbermen, who take any kind of sufficient dimensions without much discrimination regarding species. Such forests as exist are generally open and may be traversed by wagon or on horseback, and it is only on comparatively limited areas that any close or dense growth of trees is encountered. In young growths of lodgepole pine only are there what might be called thickets, and occasionally a dense growth of small red fir and its accompanying species is found on some locally favored north slope." (p. 43)*

Jack includes some 90 photographs representative of forest conditions in 1897 to 1898 (Veblen and Donnegan 2005), such as that shown in figure A.3. Other early forest descriptions can be found in Ingwall (1923), as summarized by Veblen and Donnegan (2005).

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A. VIEW NORTH OF LOST PARK CREEK, 4 OR 5 MILES FROM ITS MOUTH.

Characteristic growth of yellow pine and Douglas spruce on considerable areas never visited by lumbermen, but subjected to surface fires at various times.

Figure A.3—Photograph taken by John Jack of an area on the Pike National Forest "never visited by lumbermen" (Jack 1900), illustrating the open nature of ponderosa pine stands and a diverse stand structure. Also pictured are snags, downed wood, and an herbaceous understory.

John Marr, working in the foothills just west of Boulder, provided detailed information and descriptions of stand structures based on data he collected from 1951 to 1953 (Marr 1961) (table A.1). Although Front Range forests were already altered by the 1950s (as noted by Marr himself on several occasions in the text), the information still provides a useful snapshot of forest conditions more than 60 years ago. Further, several of his stands exhibited little sign of logging or other disturbance associated with Euro-American settlement, such as stand A-3, of which he writes, "The presence of many large and older trees suggests a relatively stable unit long free from disturbance." Other interesting notes include the following:

> *North-facing slopes support a relatively dense forest of Douglasfir and ponderosa pine; the relative abundance of the two species varies with the angle of slope, Douglasfir increasing with increase the angle. A high percentage of ponderosa pine may indicate the presence of coarser soil as well as a more gentle slope. Grassy openings are rare on north-facing slopes and indicate unusual soil conditions where they do occur… The ridgetops in this area lose altitude toward the east. Around their eastern "ends", there is a striking change in ecosystems along a single contour. Rather dense forest of Douglasfir and ponderosa pine on the north-facing slopes begins to thin out as the exposure becomes more easterly. Then Douglasfir drops out. Open forest of ponderosa pine prevails on the south-facing slope. [p. 28]*

> *Young ponderosa pine stands on more mesic sites are very dense, but trees die rapidly in the intense competition, so that stands over one hundred years old are quite open. On dry slopes, the stands of all ages are open, with a few shrubs (Ribes cereum), a sparse ground cover of bunchgrasses (Hesperochloa kingii), and a few herbs. In the typical old stand, tree crowns generally do not meet, and trees average 40 feet tall with some vigorous individuals reaching a height of 50 feet. The trees are often clumped in groups of a few individuals separated by openings with a sparse cover of herbs in a park-land type of landscape… All but a very few of the present-day ponderosa pine stands are stages of secondary succession. The few climax stands that do occur are small and occupy extreme sites. [p. 29]*

> *A very open ponderosa pine-grass stand, perhaps a true park-land type, occupied this site about 100 years ago. Tree seedlings were unsuccessful in competition with the herbs and consequently tree density was kept relatively low. Grazing by the cattle of early settlers weakened and/or partially destroyed the herb ground cover. Tree seedlings, no longer encountering severe competition, developed in abundance in years when there was a coincidence of a good seed crop and favorable spring-summer weather, but cattle destroyed or damaged many of the seedlings and few achieved the dimensions of trees. At a still later date, grazing pressure was reduced, seasonally*

Table A.1—Stand data collected by John Marr in the foothills west of Boulder, Colorado, 1953 to 1955, published in Marr (1961). The data depict greater basal area and tree density on north-facing slopes than on south-facing slopes and an increase in compositional complexity and species richness with elevation, consistent with present-day knowledge of variation in these parameters.

Elevational zone	Stand ID and type	Elevation (feet)	Exposure	Slope (%)	Shrub/ sapling cover (%)	Herb cover (%)	Basal area (square feet/ acre)	Trees per acre	Species composition (% basal area)
Lower Montane	A-1 Ponderosa pine	7,200	Ridgetop	—	1.0	12.2	66.6	460	*Pinus ponderosa* (92%) *Pseudotsuga* (6%)
	A-2 Douglas-fir—Ponderosa pine	7,200	N-facing	18	7.1	5.7	158.7	750	*Pseudotsuga* (61%) *Pinus ponderosa* (38%)
	A-3 Ponderosa pine	7,200	S-facing	18	0.8	17.7	57.5	430	*Pinus ponderosa* (99%) *Juniperus virginiana* (1%)
Upper Montane	B-1 Douglas-fir—Ponderosa pine	8,500	Ridgetop	—	9.4	9.3	56.9	NR	*Pseudotsuga* (68%) *Pinus ponderosa* (26%) *Pinus flexilis* (5%)
	B-2 Douglas-fir—Ponderosa pine	8,500	N-facing	13	29.6	11.2	77.0	1,155	*Pseudotsuga* (57%) *Pinus ponderosa* (21%) *Populus tremuloides* (12%) *Pinus flexilis* (7%) *Pinus contorta* (1%)
	B-3 Ponderosa pine—Douglas-fir	8,500	S-facing	18	4.3	45.8	9.1	132	*Pinus ponderosa* (80%) *Pseudotsuga* (11%) *Juniperus virginiana* (0.5%) *Pinus flexilis* (8%)

if not annually, and a large number of seedlings grew into saplings which subsequently formed the current dense patches of younger trees. It is possible that repeated fires rather than competition inhibited tree reproduction in this site in pre-settlement days… The low productivity of herbage and the absence of fire scars on the older trees, however, lead me to think that competition was the probable control. [p. 33]

The work of Marr (1961) was followed up by Kooiman and Linhart (1986), who resurveyed and more permanently monumented Marr's plots in 1981. Korb and Ranker (2001) followed as well, sampling the plots in 1996 and describing change from 1981 to 1996 in the context of Marr's original hypotheses about plot successional trajectories.

In the 1980s, Tom Veblen at the University of Colorado Boulder visited and photographed sites that had originally been photographed in the late 1800s and early 1900s near Boulder (fig. A.4). Veblen and Lorenz (1991) provide an extraordinary account of forest change that had occurred over nearly 100 years from the late 1800s to the mid-1980s. Veblen and Lorenz (1991) are careful to note any evident disturbances, such as fire and logging, that occurred prior to the historical photographs and that may bias the interpretation of forest change. But they generally document an increase in stand densities that has occurred in lower montane forests in Boulder County in the 20th century. They also document the occurrence of high-severity fires in montane forests in the 19th century that predate any possible effects of fire exclusion.

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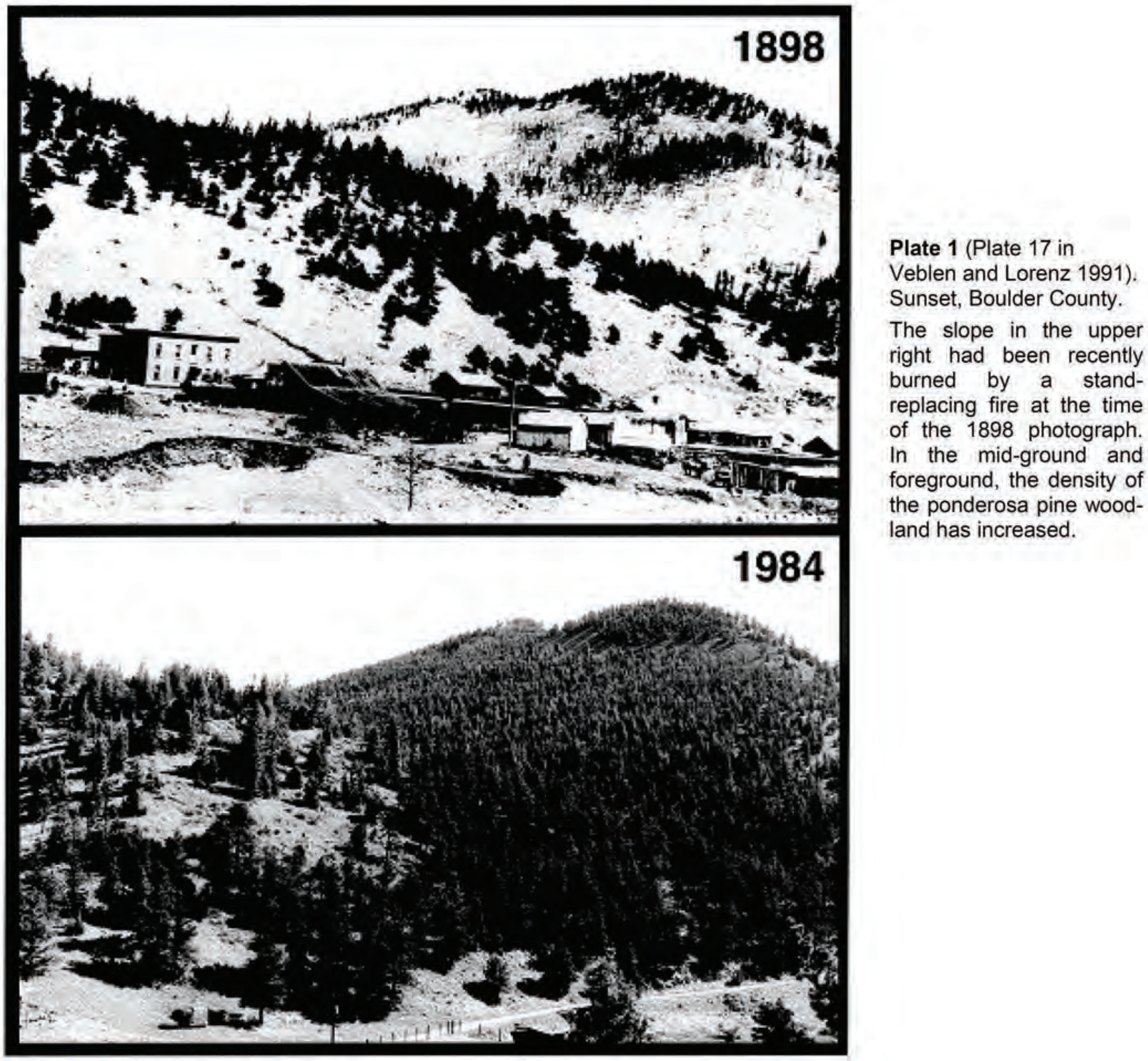
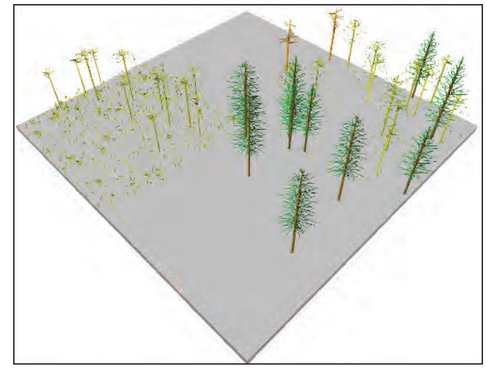
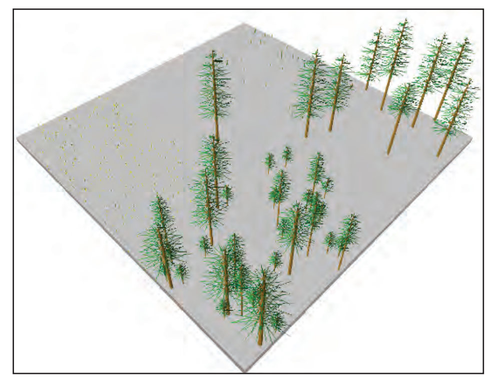
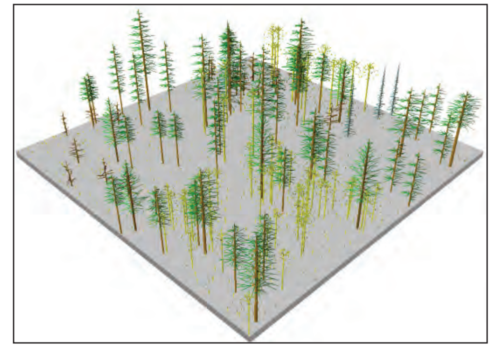
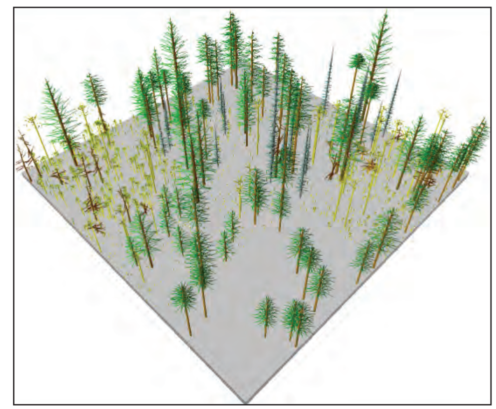


Figure A.4—Example photo-sequence from Veblen and Lorenz (1991) depicting forest conditions in 1898 and again in 1984 near Boulder, Colorado.

Appendix B—Stand Density Matrix Representing Variable Residual Densities Within a Single Treatment Unit (adapted from the Upper Monument Creek Design Criteria Appendix D; Upper Monument Creek Collaborative 2014).

Structure	BA[a]	Description	Example photo	Stand visualization
Openings	0–20	Openings ranging in size from 0.25 to tens of acres are appropriate in low-productivity settings within the treatment unit. Openings may contain small amounts of residual tree cover. Openings are expected to stimulate understory vegetation growth, and may result in the establishment of conifer seedlings and aspen sprouts.		
Low-density matrix	20–40	A low-density woodland matrix is appropriate along ridges, south-facing slopes, and other low-productivity areas within the treatment area. Ponderosa pine is likely to dominate these areas, and the desired structure is open woodland characterized by tree groups, scattered individual trees, and openings. Residual trees should be variably spaced. Existing tree groups (i.e., trees having interlocking crowns) should be enhanced by clearing around them. Tree groups may contain anywhere from 2 to 10+ trees, but most are likely to contain around 2 to 5 trees.		

Structure	BA[a]	Description	Example photo	Stand visualization
Medium-density matrix	40–60	A medium-density woodland matrix is appropriate for mid-slopes and other areas of intermediate productivity. Enhance spatial structure by focusing on tree groups, individual scattered trees, and openings. Average distance between tree groups may be less in this case (around 1 tree length), and the proportion of trees that occur in groups versus scattered individual trees should increase as well. About 70 to 90 percent of trees may occur in groups and group size may be larger as well, typically on the order of 5 to 9 trees per group.		
High-density matrix	80+	A high-density forest matrix is appropriate on north-facing slopes and other moist, higher-productivity areas. Douglas-fir is naturally more prevalent in these areas. The characteristic structure of lower-density settings (i.e., tree groups, individual scattered trees, and openings) may be less evident at this density as most trees occur in groups (90+ percent) and fewer as scattered individuals. Treatments in this setting may involve mild reductions in density by thinning from below or hand-felling of small-diameter stems and ladder fuels.		

[a] BA = basal area in square feet/acre.

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