Submitted to Springer for publication in book:
McKenzie, Donald; Miller, Carol; Falk, Donald A. 2011. The landscape ecology of fire. Doerdrecht, The Netherlands; London, United Kingdom; Heidelberg, Germany; New York, USA: Springer Science+Media B.V. 312 p.312

10. Managing and Adapting to Changing Fire Regimes in a Warmer Climate

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Planning and management for the expected effects of climate change on natural resources are just now beginning in the western United States (U.S.), where the majority of public lands are located. Federal and state agencies have been slow to address climate change as a factor in resource production objectives, planning strategies, and on-the-ground applications. The recent assessment by the Intergovernmental Panel on Climate Change (IPCC 2007) and other high-profile reports (e.g., GAO 2007) have increased awareness of the need to incorporate climate change into resource management.

Most of the recent literature on adaptation to climate change has focused on conceptual issues (Hansen et al. 2003; Adger et al. 2005), potential actions by local governments and municipalities (Snover et al. 2007), and individual resources and facilities (Slaughter and Wiener 2007). However, efforts to develop strategies that facilitate adaptation to documented and expected responses of natural resources to climate change are now beginning in earnest. For example, the Chief of the U.S. Forest Service recently stated that addressing climate change is one of the top three priorities of the agency (Kimbell 2008). In the most substantive effort to date, the U.S. Climate Change Science Program has developed synthesis and adaptation products for federal land management agencies (Joyce et al. 2008).

The frequency, severity, and extent of wildfire are strongly related to climate (Swetnam and Betancourt 1990; Johnson and Wowchuk 1993; Stocks et al. 1998; Hessl et al. 2004; Gedalof et al. 2005; Heyerdahl et al. 2008; Skinner et al. 2008; Taylor et al. 2008; Littell et al. 2009). Increasing temperatures with climate change will likely lead to changes in fire regimes in many types of ecosystems (IPCC 2007). Increased spring and summer temperatures with climate change will lead to relatively early snowmelt (Stewart et al. 2005; Hamlet et al. 2007), lower summer soil moisture (Miles et al. 2007) and fuel moisture (Westerling et al. 2006), and longer fire seasons (Wotton and Flannigan 1993; Westerling et al. 2006). These conditions will lead to increased fire frequency and extent (Price and Rind 1994; Gillett et al. 2004; Westerling et al. 2006). McKenzie et al. (2004) found that for a mean temperature increase of 2°C (expected by mid-21st century), annual area burned by wildfire is expected to increase by a factor of 1.4 to 5 for most western U.S. states. Dry fuel conditions associated with increased temperatures allow forests to burn whenever an ignition source occurs, with low humidity and high winds contributing to fire spread.

Climate change will alter the effectiveness of fire and fuel management, and therefore necessitates that we adapt how we manage fire and fuels. There are well established scientific principles of fuels management upon which we can rely to

inform future strategies. These strategies need to be applied to large landscapes, which are the land units for which managers are responsible and across which fires spread. Adaptation to changing fire regimes and other ecological effects of climate change will help reduce ecosystem vulnerabilities and potentially undesirable effects on ecosystem composition, structure, and function (Millar et al. 2007; Joyce et al. 2008).

Adapting management to changing fire regimes will likely be a major challenge for resource managers in the face of climate change. This chapter outlines general adaptation strategies and specific fire and fuel management options for forest managers under climate change, primarily for dry forests with low-severity and mixed-severity fire regimes (e.g., pinyon pine-juniper [*Pinus* spp., *Juniperus* spp.], ponderosa pine [*Pinus ponderosa*], dry Douglas-fir [*Pseudotsuga menziesii*], mixed conifer, mixed evergreen). We first present strategies and options from the perspective of managers and then expand on some of these from the perspective of research.

10.1 Adapting to the Effects of Climate Change

We initiated science-management collaborations at Olympic National Forest (Washington, USA) and Tahoe National Forest (California, USA) to develop management options that will facilitate adaptation to climate change (Littell et al., n.d.). This was the first attempt to work with national forests to develop specific concepts and applications that could potentially be implemented in management and planning. The focus of this effort was to develop strategies and management options for adapting to climate change across multiple resources, and there was no intention to specifically focus on fire or fuels management. In this chapter, we build on this foundation of general concepts by identifying strategies and management options relevant for managing changing fire regimes across large landscapes.

10.1.1 General Adaptation Strategies

The national forests developed six *general adaptation strategies* (Table 10.1; Littell et al., n.d.) in response to climate change. We have amended these strategies to emphasize their relevance for landscape fire and fuels management in a changing climate:

- Manage for resilience, decrease vulnerability–Fire exclusion has increased understory vegetation and surface fuels in many forests, making them vulnerable to crown fire should wildfire occur. Managing for reduced understory and sur-

face fuels will increase resilience to fire and favor retention of large trees (Dale et al. 2001; Peterson et al. 2005; Joyce et al. 2008). Thinning, surface fuel removal (mechanically or through prescribed burning), and allowing naturally ignited fires to burn (rather than suppressing them) can reduce fuels across sufficient areas to reduce the severity of future wildfires.

- Implement climate-smart treatments—Managers have many choices for treating landscapes, but typically have minimal financial and human resources, so prioritizing treatments that are likely to work in a warmer climate may become increasingly necessary (Millar et al. 2007). For example, stand densities may need to be lower in the future to reduce the risk of overstory mortality if fire weather will be more extreme (Dale et al. 2001; Spittlehouse and Stewart 2003). Reduced stand densities would also increase resistance to drought and insect attack.
- Consider tradeoffs and conflicts—Future effects on ecological and socioeconomic sensitivities can result in potential tradeoffs and conflicts for species conservation and other resource values. For example, forest landscapes with periodic thinning and surface fuel treatments may have different carbon dynamics than landscapes without active management in which crown fires would be more likely to occur (Millar et al. 2007; Hurteau et al. 2008).
- Manage dynamically and experimentally—Currently-available opportunities (i.e., under current policy) can be used to implement adaptive management over several decades (Dale et al. 2001). For example, different types and intensities of fuel treatments can be used over time and space in order to determine their effectiveness for reducing crown fire.
- Manage for process—Project planning and management can be used to maintain or enhance ecological processes rather than to design specific structures or species composition (Harris et al. 2006). For example, novel mixes of species and spacing can be used following fire in order to reflect likely natural dynamic processes of adaptation.
- Manage for realistic outcomes—Projects that are currently a component of the planning process may have a higher failure rate in a warmer climate, and it will become increasingly important to assess the viability of management goals and desired outcomes (Hobbs et al. 2006). For example, it will never be possible to eliminate fire from wildland-urban interface areas, but land managers can work with local residents to reduce fire hazard to a level that may allow suppression to be effective there, while allowing fire to play a less managed role in other parts of the landscape.

10.1.2 Specific Adaptation Options

The national forests developed nine *specific adaptation options* (Table 10.2). In contrast to the guiding principles provided by general strategies above, adaptation

options refer to specific kinds of actions that can be taken at a variety of spatial scales. We have amended the discussion to emphasize the relevance of those options for fire:

- Increase landscape diversity—This option focuses on increasing variety in stand structures and species assemblages over large areas and avoiding "one size fits all" management prescriptions (Millar et al. 2007). This can include applying forest thinning to increase variability in stand structure, increase resilience to stress by increasing tree vigor, and reduce vulnerability to disturbance (Parker et al. 2000; Dale et al. 2001; Spittlehouse and Stewart 2003). Although there is no theory or empirical data at the present time to guide which combinations of stand structures and species will optimize adaptation potential, allowing fires to burn unsuppressed may in some cases help to emulate landscape patterns that existed during pre-settlement times (Hessburg and Agee 2003). These patterns from natural experiments may hold the greatest adaptation potential.
- Maintain biological diversity—Appropriate species and genotypes can be planted in anticipation of a warmer climate (Smith and Lenhart 1996; Parker et al. 2000; Noss 2001; Spittlehouse and Stewart 2003; Millar et al. 2007), giving more flexibility by diversifying the phenotypic and genotypic template on which climate and competition interact, and to avoid widespread mortality at the regeneration stage. For example, nursery stock from warmer drier locations than what is prescribed in genetic guidelines based on current seed zones can be planted following a crown fire (Spittlehouse and Stewart 2003).
- Increase resilience at large spatial scales—Proactive management can improve the resilience of natural resources to ecological disturbance and environmental stressors (Dale et al. 2001; Spittlehouse and Stewart 2003; Millar et al. 2007) and reduce the number of situations in which land managers must respond in "crisis mode." For example, if hazardous fuels reduction and allowing some fires to burn unsuppressed reduces fire severity over large areas, then postfire soil erosion can be minimized.
- Treat large-scale disturbance as a management opportunity—Large-scale disturbance causes rapid changes in ecosystems, but also provides opportunities to apply adaptation strategies (Dale et al. 2001; Millar et al. 2007). Carefully designed management experiments for adapting to climate change can be implemented, provided that plans are in place in anticipation of large disturbances. For example, one could experiment with mixed-species tree planting after fire even though the standard prescription might be for a monoculture (Millar et al. 2007). Management experiments need good statistical design, adequate replication, and long-term commitment by managers and scientists to maintain a time series of data that can inform future decisions.
- Increase management unit size—Increasing the size of management units to hundreds or thousands of hectares across logical biogeographic entities such as watersheds will improve the likelihood of accomplishing objectives (Smith and

Lenhart 1996). For example, large strategically located blocks of forest land subjected to fuel treatments will reduce fire spread more effectively than smaller dispersed units (Finney 2001). At the present time, there is minimal theory or empirical data to guide the design the size and spatial patterns of management units, although a closer approximation of patch size created by natural disturbances may be a good place to start.

- Implement early detection/rapid response for invasive species—A focus on treating small problems before they become large unsolvable problems recognizes that proactive management is more effective than delayed implementation (Millar et al. 2007). For example, recently burned areas are often susceptible to the spread of invasive species, which can be detected by monitoring during the first two years after fire.
- Match engineering of infrastructure to expected future conditions—This refers primarily to road and drainage engineering that can accommodate future changes in hydrology (Spittlehouse and Stewart 2003). However, it might be possible to design road networks to facilitate effective fire suppression in areas that are particularly fire prone.
- Collaborate with a variety of partners—Working with a diversity of landowners, agencies, and stakeholders will develop support for and consistency in adaptation options. For example, national forest managers can work with adjacent state forest managers to agree on fuel treatment plans across large landscapes.
- Promote education and awareness about climate change—It is critical that internal and external education on climate change is scientifically credible and consistent (Spittlehouse and Stewart 2003), with emphasis on the role of active management in adaptation. For example, local residents can be informed that wildfire may be more frequent in a warmer climate, which makes it imperative that they clear brush around homes to reduce fire hazard.

Effective landscape fire and fuel management will require that we consider the potential effects of climate change and adjust activities accordingly. Much of the current dialog among scientists and resource managers about adapting to climate change in general is relevant and applicable to landscape fire and fuel management. Despite considerable uncertainty about the effects of climate change, scientific foundations for adaptation are sufficiently developed to begin the adaptation process. By taking an experimental and learning approach to management it will be possible to be both adaptive and responsive.

10.2 Fuels Management in a Warmer Climate

The expected warming in climate may have implications for the design of fuel treatments in dry forests across the western United States. Climate change will in-

fluence fire behavior by increasing temperature, an important factor that controls fire behavior. Temperature regulates several variables that control fuel flammability: relative humidity of the atmosphere, moisture content of dead and live fuel, and wind speed and direction in mountainous terrain (Brown and Davis 1973). Foliar moisture controls fire behavior and thresholds for crown fire initiation (Agee et al. 2002). For example, a closed-canopy stand is typically cooler and has higher humidity than an open stand. These characteristics retain dead and live fuel moisture, which regulates surface fuel temperature and wind speeds (Whelan 1995), although closed-canopy stands often have low canopy base height and high canopy bulk density, both of which increase the probability of crown fire initiation. On the other hand, lowering tree density decreases the probability of crown fire initiation, but may exacerbate fire behavior because solar radiation to the forest floor can desiccate dead and live fuels (Agee and Skinner 2005).

Based on these considerations, fuel treatment guidelines for restoring the resilience of dry forest ecosystems (e.g., Peterson et al. 2005) may need to be adjusted to retain either more or fewer stems per hectare (Harrod et al. 1999; Arno and Allison-Bunnell 2002; Johnson 2008). Forest managers may want to weigh the tradeoffs related to each strategy for their particular project (Peterson and Johnson 2007) and decide which treatment is feasible for addressing the effects of a warmer climate on fuels and fire hazard. Understanding basic concepts of fuels and how to manage them for landscape resilience, and having a way to evaluate effectiveness of fuel treatments, is a good combination for sustainable management at large spatial scales.

10.2.1 Fuel Concepts and Fire Resilience

Fuel is a critical component of both the combustion triangle (fuel, oxygen, heat) and the fire behavior triangle (weather, fuel, topography), which are conceptual aids for understanding the principles of combustion and the elements that influence fire behavior and intensity (Brown and Davis 1973; Pyne et al. 1996). Fuel is classified by its vertical distribution (ground, surface, or aerial) and its general properties within a stand (Ottmar et al. 2007). Ground fuels (e.g., decomposing organic matter, rotting logs) have little influence on wildfire spread. Fire spreads primarily in the surface fuels, which include seedlings and saplings (i.e., trees less than 1.8 m tall), shrubs, herbaceous vegetation, litter, and dead woody material (Brown and Davis 1973). Aerial or crown fuels are composed of live and dead vegetation. Collectively, these fuel layers are referred to as a fuelbed, which represents the average physical characteristics of a relatively homogeneous unit on a landscape with distinct fire environments (Sandberg et al. 2007). Dead woody fuel is classified by fuel moisture time lags (Fosberg and Deeming 1971). In general, small diameter fuels have short time lags and are responsible for fire spread rates. Large diameter fuels have longer time lags and are involved primarily in

smoldering. The type of fuel within a fuelbed strongly influences the intensity of wildfire.

The scientific basis for using fuel treatments to maintain or restore resilience to wildfire in dry forests is well established (Peterson et al. 2005) and has provided support for thinning and surface fuel treatments throughout western North America (Fig. 10.1), including for adaptation to a warmer climate (Joyce et al. 2008). Agee and Skinner (2005) developed four principles of a fire-safe forest: (1) reduce surface fuels, (2) increase height to live crown, (3) decrease crown bulk density, and (4) retain large trees (Table 10.3). Surface fuels can be reduced with treatments such as prescribed fire, pile and burn, and whole-tree harvest. Increasing the height to live crown and decreasing crown bulk density can be achieved by thinning from below (progressively removing trees with the smallest diameter). Fuel reduction treatments designed to leave the large fire resistant trees fulfill the fourth principle of a fire-safe forest. Agee and Skinner (2005) concluded that forests treated according to these principles will be more resilient to wildfires in a warmer climate. In some cases, it may be possible to accomplish fire-safe principles by allowing wildfires to burn unimpeded through areas that have not burned for decades (Miller et al., Chap. 11), although postfire stem density, quantity of fuel removed, and spatial patterns of altered stand and fuel structure cannot be controlled.

Place Figure 10.1 here

Although resilience to fire can be enhanced with fuel treatments, climate is a major driver of fire regimes (Gedalof et al. 2005; Littell et al. 2009), and fuel treatment effectiveness is reduced when fires burn under severe conditions (high temperature, high wind speed, low humidity). In some cases, the influence of climate on fire could override fuel treatments, resulting in high-severity fire even in areas where fuels have been reduced. The relative influence of climate versus fuels on fire regimes is specific to the type of ecosystem being considered. For example, boreal forests and subalpine forests typically always have fuel loadings that are sufficiently high to carry fire and potentially propagate crown fires, but high temperature and low humidity are necessary to dry the fuels so they can burn; therefore, climate limits fire regimes in these forests. In contrast, ponderosa pine forests in the American Southwest are hot and dry every summer, but must have sufficient surface fuels to carry fire; therefore, fuels limit fire regimes in these forests. Understanding differences in these relative influences among ecosystems will help to develop and evaluate effective fuel management prescriptions.

10.2.2 Evaluating Effectiveness with Fire Simulation Models

Fire simulation models are valuable for testing the efficacy of fuel treatments, especially given the logistic challenges of conducting large-scale field experiments (Andrews and Queen 2001). For example, Johnson (2008) simulated the effects of thinning and surface fuel treatments on fire hazard using the Fire and Fuels Extension to the Forest Vegetation Simulation (FFE-FVS: Reinhardt and Crookston 2005) on 45,162 stands from dry forests in the western United States. Treatments were patterned after Agee and Skinner's (2005) principles of a fire-safe forest. Stands were evaluated for four thinning densities (125, 250, 500, and 750 trees per hectare [tph]), three surface fuel treatments (leave slash, extract slash, prescribed fire) and no action, resulting in a total of 698,140 projections.

Results indicate that thinning treatments with lower target densities (125 and 250 tph) are more effective at modifying fire behavior than treatments with higher target densities (500 and 750 tph). These results are consistent with those from other studies (Stephens 1998; Harrod et al. 1999; Agee et al. 2000; Pollet and Omi 2002; Martinson and Omi 2003; Finney et al. 2005; Stephens and Moghaddas 2005; Cram et al. 2006; Harrod et al. 2007; Strom and Fulé 2007). Arno and Allison-Bunnell (2002) suggested that historical surface fire regimes perpetuated ponderosa pine-dominated stands with 75–250 tph, that is, stands of similar density to those simulated in Johnson (2008). In other studies, 125 tph represented historical stands in eastern Washington (Harrod et al. 1999), 100 tph was typical for Southwestern stands (Covington and Moore 1994), and 150 tph was found in old Jeffrey pine-mixed conifer forests in the unmanaged Sierra San Pedro Martir (Mexico) (Stephens and Gill 2005).

Fuel treatment guidelines for dry forests in the western United States have been developed based on output from the simulation model FFE-FVS (Johnson et al. 2007). We use an example from that publication—a forest stand in the Okanogan-Wenatchee National Forest in Washington State—to illustrate how different thinning options can be evaluated (Table 10.4; Fig. 10.2). The stand is composed of 6,154 tph, dominated by Douglas-fir and ponderosa pine. FFE-FVS predicted passive crown fire under severe weather. Before treatment, canopy base height was 0.6 m, and canopy bulk 500, and 750 tph. The 125 and 250 tph thinning treatments were more effective than the other treatments because they prevented crown fire initiation by reducing ladder fuels within the stand. The 125 and 250 tph thinning treatments generated the highest torching indices, highest canopy base heights, and lowest canopy bulk densities. The 125 tph treatment produced the lowest basal area mortality.

Place Figure 10.2 here

The lower stand densities plus lower surface fuel loads identified above will probably be necessary to confer resilience in dry forests in the face of more severe

fire weather. This will tend to reduce the severity of wildfire, and will allow longer periods of time between thinning treatments needed to maintain low fuels. In some forests, caution is needed that stand densities not be reduced to a level that will allow rapid growth of understory vegetation that could increase fire hazard (e.g., Thompson et al. 2007).

10.2.3 Landscape Considerations for Fire and Fuels Management

Stand-based treatments and evaluations will be more effective when applied in the context of a strategic plan for large landscapes. Therefore, a major challenge in fire management is to determine the optimal placement and size of fuel treatments on the landscape. Fuel treatments are not intended to stop a wildfire, but they can alter fire behavior (Finney and Cohen 2003). Fire managers do not have the capacity or resources to treat all areas that need to be thinned, because of land ownership, conflicting management objectives, and funding limitations (Finney 2007). Given these constraints, decisions about location and size of treatments can be explored with optimization models (e.g., Finney 2007), expert knowledge of local landscapes (Peterson and Johnson 2007), and examination of spatial patterns of forest structure and fuels over large landscapes over time (Fig. 10.3). In general, placement of treatments is designed to create landscape patterns that deter wildfire spread and modify fire behavior, while minimizing area needed for treatment (Finney 2001; Hirsch et al. 2001). Some modeling tools have options for determining the spatial arrangement and placement of fuel treatments. For example, Finney (2007) developed an algorithm to locate the specific treatment areas that reduce fire growth by the greatest amount for target environmental conditions. This type of modeling tool is the first step in developing an application that will help managers to determine the best location to place treatments with the goal of reducing wildfire behavior across a landscape.

Place Figure 10.3 here

Millions of hectares of public and private land would benefit from thinning treatments and surface fuel removal to reduce wildfire behavior (U.S. Forest Service 2000), but they are often not treated because of cost, potential (for prescribed burning) to cause air pollution, lack of safe periods for (prescribed burning) treatment, and esthetic reasons (Rummer 2008). Cost is related to two forms of treatment, *in situ* and extraction. *In situ* operations are designed to change the structure and arrangement of fuel loads and involve activities such as prescribed fire, mastication, or pile-and-burn. Extraction is the removal of fuels and usually costs considerably more than *in situ* methods unless the material removed has economic value. The cost of a project can be calculated from expert opinion, total bid cost, financial records of total enterprise costs, and economic analysis of fixed and vari-

able costs (Keegan et al. 2002; Rummer 2008). Regardless of the methods used for treatment and cost calculation, it may become increasingly difficult for resource managers to treat sufficient area to significantly affect fire spread and behavior in a warmer climate.

Fuel treatments can have unintended consequences on other forest resources. For example, thinning and surface fuel treatments can provide an avenue for propagation of exotic plant species (Crawford et al. 2001; Griffis et al. 2001). Prescribed fire can scorch the crowns of live trees, which may increase stress or tree mortality (Graham et al. 2004). However, the biggest effect of fuel treatments is often on wildlife habitat (Randall-Parker and Miller 2002), with animal species that depend on complex forest structure being negatively affected (Pillod et al. 2006). For example, a fuelbed structure that prevents crown fire initiation may decrease habitat for species that depend on large patches of dense multi-story forest (e.g., many species of neotropical migrant birds). Alternatively, species that forage in open forest structure (e.g., ungulates) may benefit from fuel treatments. Accounting for this interaction among resources will be a challenging consideration in fuel treatment planning in a warmer climate, because a warmer climate may directly affect those individual resources as well as the interactions.

10.3 Conclusions

The current warming trend in northern latitudes will almost certainly lead to increased wildfire area in most ecosystems, with associated effects on ecosystem structure and function. Fuels will be flammable for longer periods of time. Prolonged droughts and insect attacks may increase fuel loads, leading to increases in fire hazard and potential fire severity. Exotic plants could further alter fire regimes in some ecosystems (Keeley et al., Chap. 8), challenging our ability to manage for resilient and sustainable landscapes. A warmer and dryer climate will reduce the effectiveness of fuel treatments in some locations. In these cases, using disturbance events such as wildfire as opportunities to influence species composition for resilience to climate change may be the best adaptation option.

Incorporating potential climate change effects and strategies into management plans will be a key step for agencies and organizations in adapting to climate change. Planning for potential impacts of climate change will increase preparedness, allow for time-efficient response to the effects of climate change, and minimize economic and ecological costs.

Many resource managers consider the current political and regulatory environment for managing national forests to be a severe limitation on adaptation to climate change (Joyce et al. 2008; Littell et al., n.d.). Policies, regulations, and administrative guidelines, though well intended for various conservation objectives, often fail to incorporate climate change and therefore focus on static (e.g., historic range of variation) rather than dynamic resource objectives. Lengthy planning, re-

view, and approval processes can delay timely implementation of management actions (e.g., following a large wildfire) that could facilitate adaptation. Some of these constraints can be overcome by institutionalizing science-management partnerships in order to develop guidelines for addressing fire issues in a warmer climate. Incorporating climate change explicitly into national, regional, and national forest policy would be a major step forward in implementing climate change in established planning processes. "Climate-smart" policies and regulations that provide guidance but allow for local forest-level strategies and management actions that increase resilience and reduce vulnerability to climate change would also promote adaptation. Educational efforts to promote awareness of climate change will help create a more consistent approach within land management agencies and encourage support from stakeholders for fire and fuels management that facilitates adaptation to climate change.

We are optimistic about future opportunities to adapt to climate change with respect to fire. First, a familiar conceptual framework such as adaptive management can be used to facilitate fire and fuels management in a warmer climate. Second, there appears to be a core set of management strategies on which adaptation to climate change in national forests can be based (Table 10.1) (Millar et al. 2007; Joyce et al. 2008; Littell et al., n.d.). Third, it appears that resource managers with professional expertise on local landscapes can develop viable options for adapting to climate change if scientists can provide the scientific basis for decision making (Table 10.2). The scientific basis for managing fuels to enhance resilience already exists (Table 10.3) but will need to be continually tested for application to large landscapes. Such testing can initially be done in the simulation environment, but judicious and cautious experimentation by management will likely provide the greatest opportunities for adaptation and learning.

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Table 10.1. Summary of general adaptation strategies, and examples of applying those strategies to changing fire regimes

Adaptation strategy	Examples of application to changing fire regimes
Manage for resilience, decrease vulnerability	Reduce stem density and surface fuel in stands where fire exclusion has created vulnerability to crown fire.
	Implement fuel treatments across large landscapes in order to modify fire severity and spread.
Prioritize climate-smart treatments	Design fuel treatments to be resilient to intense fire behavior that may accompany extreme fire weather in the future.
Consider tradeoffs and conflicts	Identify how fuel treatments may affect carbon dynamics, hydrology, and wildlife habitat at various spatial and temporal scales.
Manage dynamically and experimentally	Implement various types and intensities of fuel treatments at different spatial and temporal scales and evaluate their effectiveness for reducing crown fire.
Manage for process	Plan for the regular occurrence of wildfire at different spatial and temporal scales, rather than only suppressing fire or considering it to be an anomaly.
Manage for realistic outcomes	Plan for the regular occurrence of fire, not elimination of fire in wildland-urban interface areas.
	Develop collaborative management between public land managers and local residents to modify fuels sufficiently to reduce fire severity if wildfire occurs and to facilitate suppression.

Table 10.2. Summary of specific adaptation options developed by National Forests, and examples of applying those options to changing fire regimes

Adaptation option	Examples of application to changing fire regimes
Increase landscape diversity	Thin forest stands to create lower density, diverse stand structures and species assemblages that reduce fire hazard, increase resilience to wildfire (allow overstory survival), and increase tree vigor by reducing competition.
Maintain biological diversity	Plant nursery stock from warmer, drier locations than what is prescribed in genetic guidelines based on current seed zones.
	Plant mixed species and genotypes, with emphasis on fire resistant species and morphology.
Increase resilience at large spatial scales	Implement thinning and surface fuel treatments across large portions of landscapes (e.g., large watersheds) where large wildfires may occur.
	Orient the location of treatments in sufficiently large blocks to modify fire severity and fire spread.
Treat large-scale disturbance as a management opportunity	Develop plans for management objectives and activities following large fires, including long-term experimentation.
Increase management unit size	Focus the spatial scale of management on units (or aggregated units) of hundreds to thousands of hectares in appropriate geographic locations.
	Implement fuel treatments across large units and blocks of land to more effectively reduce fire severity and spread.
Implement early detection / rapid response for exotic species	Survey and monitor vegetation following wildfire in order to detect and eradicate undesirable invasive plant species.
Match engineering of infrastructure to expected future conditions	Modify drainage systems (e.g., install larger culverts) to accommodate higher water flow resulting from more wildfire.
	Design road systems to facilitate efficient fire suppression.
Collaborate with a variety of partners	Develop mutual plans for fire and fuels management with adjacent landowners to ensure consistency and effectiveness across large landscapes.
Promote education and awareness about climate change	Facilitate discussion among management staff regarding the effects of a warmer climate on fire and interactions with multiple resources.
	Educate local residents about how a warmer climate will increase fire frequency, fuel reduction can protect property and collaboration with public land managers will assist broader fuel management objectives.

Table 10.3. Principles of fire resistance for dry forests. Adapted from Agee (2002) and Hessburg and Agee (2003)

Principle	Effect	Advantage	Concerns
Reduce surface fuels	Reduces potential flame length	Fire control easier; less torching of individual trees	Surface disturbance less with fire than other mechanical techniques
Increase height to live crown	Requires longer flame length to begin torching	Less torching of individual trees	Opens understory; may allow surface wind to increase
Decrease crown density	Makes tree-to-tree crown fire less likely	Reduces crown fire potential	Surface wind may increase; surface fuels may be drier
Keep big trees of resistant species	Less mortality for same fire intensity	Generally maintains overstory structure	Less economical; may keep trees at risk of insect attack

Table 10.4. Effects of thinning and surface fuel treatments on fire hazard on a stand in the Okanogan-Wenatchee National Forest, as simulated in the Fire and Fuels Extension to the Forest Vegetation Simulator. Adapted from Johnson et al. (2007)

	Thinning treatments (trees ha^{-1})				
Parameters	Initial	125	250	500	750
Torching index (km h^{-1})	0	130	42	19	27
Basal area mortality (%)	7	20	30	21	70
Canopy bulk density (kg m^{-3})	0.08	0.04	0.05	0.07	0.07
Canopy base height (m)	0.6	12.5	7.0	1.8	1.5
Surface fuels[1] (Mg ha^{-1})					
0-7.6 cm	6.6	22.0	26.4	30.8	30.8
7.6-15.2 cm	8.8	13.2	17.6	19.8	17.6
15.2-30.4 cm	8.8	8.8	6.6	6.6	4.4
> 30.4 cm	0	0	0	0	0
Litter	4.4	8.8	8.8	11.0	11.0
Duff	26.4	22.0	19.8	17.6	15.4

[1] FFE-FVS assigned the initial fuel loading for each fuel component and size class.

Fig. 10.1. Removal of smaller trees and surface fuels can potentially reduce the severity of fire behavior and effects in a wildfire. Reduction of stand density and surface fuels is shown in these photos of a ponderosa pine stand on the Lassen National Forest, California, before (a) and after (b) treatment. Lower stand densities and fuels can enhance resilience to fire in a warmer climate by reducing risk of crown fire and protecting overstory trees and forest structure. Photos courtesy of Lassen National Forest.

Fig. 10.2. Visualizations of thinning for a stand in the Okanogan-Wenatchee National Forest, as simulated in the Fire and Fuels Extension to the Forest Vegetation Simulator. Initial conditions and four post-thinning stand densities (trees ha^{-1}= tph). (a) Initial conditions, (b) thinned to 750 tph, (c) thinned to 500 tph, (d) thinned to 250 tph, (e) thinned to 125 tph. Adapted from Johnson et al. (2007). See Table 10.4 for stand and fuel characteristics.

Fig. 10.3. Fuel treatment planning can be improved by quantifying stand structural conditions and fuels across large landscapes over time. Simulation tools can be used to examine the effects, placement, and visual appearance of thinning and fuel treatments throughout stand development. As stand conditions change from pretreatment (2000) to treatment + regeneration (2015) to re-growth (2030), subtle changes in landscape pattern and structure ensue (seen in the 3 landscape views.)

Figure 10.1a

Figure 10.1b

Figure 10.2

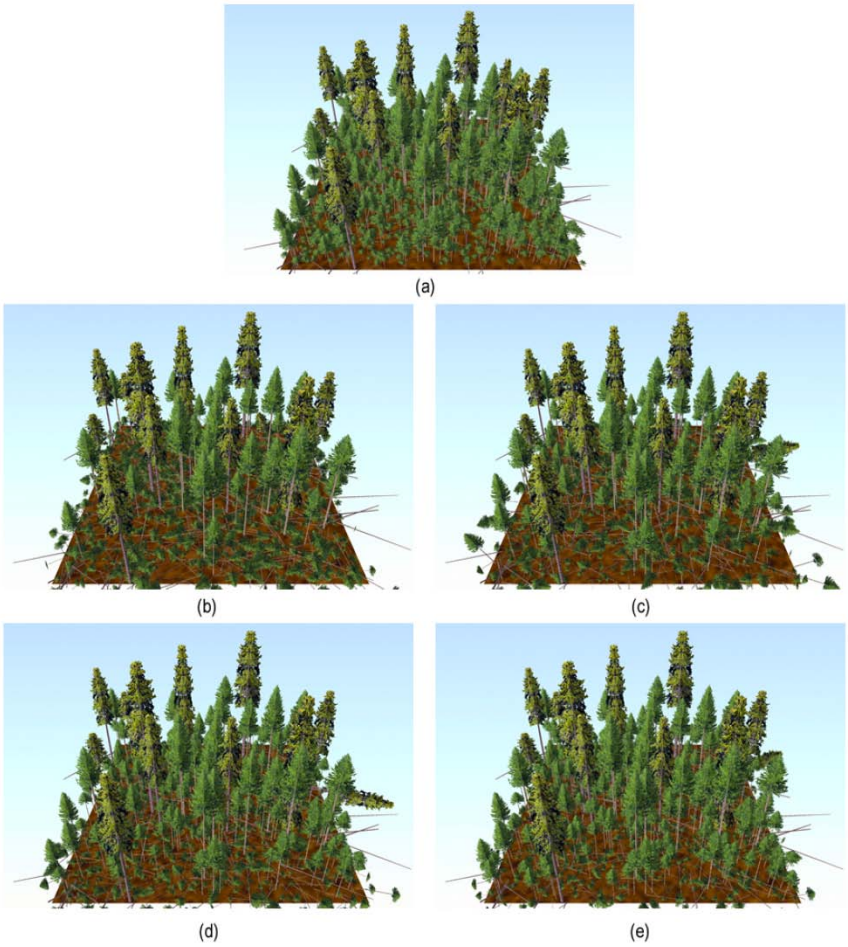
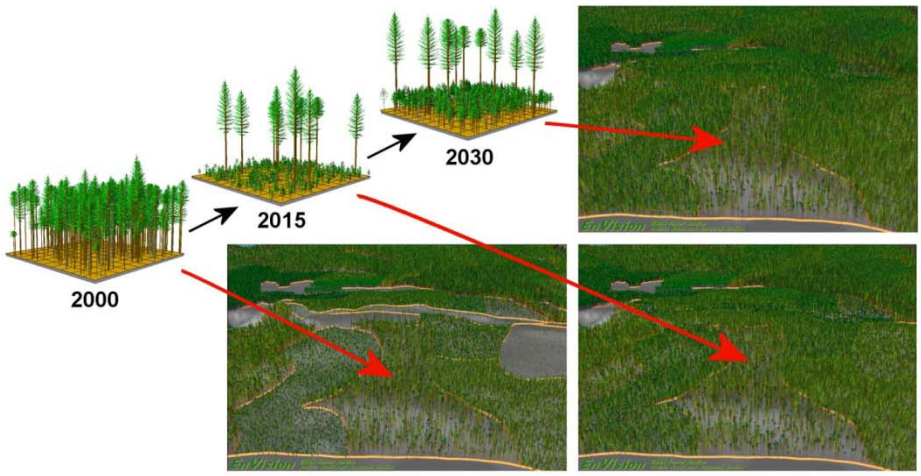
Figure 10.3