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Wildland Fuel Treatments

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Synonyms

Fuel break; Fuel hazard reduction treatments; Fuel reduction treatment; Hazardous fuel reduction treatment; Shaded fuel break

Definition

The purposeful use of any silvicultural method, including mechanical methods, managed wildfire, prescribed fire, or a combination of approaches, to intentionally alter the fuel complex in such a way as to modify fire behavior and thereby minimize the potential negative impacts of future wildfires on ecosystem goods and services, cultural resources, and human communities

Introduction

Alterations to the wildland fuel complex due to past land management practices along with a changing climate have resulted in profound changes in forest structure and wildland fuel loads in ecosystems around the world (Brown and Smith 2000; Schelhaas et al. 2003; Keeley et al. 2011). Alterations to forest structure and fuel load are particularly concerning to fire managers because they are associated with increases in the extent, behavior, severity, and complexity of wildland fires (Covington et al. 1997; Fry and Stephens 2006; Flannigan et al. 2009). Changes in the fuel complex and associated fire behavior are particularly pronounced in seasonally dry forest types that historically had frequent low to moderate intensity fire regimes (Covington and Moore 1994; Stephens and Fulé 2005; Hessburg et al. 2005). In an effort to reduce the potential risk posed by altered fuel complexes, land managers are increasingly implementing wildland fuel treatments.

The emergence of wildland fuel treatments as a key land management tool is in part because fuels are the only component of the fire behavior triangle (i.e., fuels, weather, and topography) that can be directly manipulated through management actions. Here we define a wildland fuel treatment as any purposeful use of silvicultural methods, including mechanical methods, managed wildfire, prescribed fire, or a combination of approaches that intentionally alter the fuel complex in such a way as to modify fire behavior and minimize any

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undesired wildfire impacts. Designing wildland fuel treatments requires land managers to deliberately develop plans that describe the specific targets related to the desired forest structure. This process generally requires land managers to define the project scope, identify and define goals and objectives, develop and evaluate the effectiveness of various designs, and ultimately identify a design that accomplish the goals in a timely and economically viable manor (Jain et al. 2012). The selected design is then converted to a treatment prescription which specifies the type and intensity of the activities to be to meet the stated goals and objectives.

Principles of Wildland Fuel Treatments at Stand Scales

Conventionally wildland fuel treatments are implemented at the scale of individual stands. Stands generally range from less than 10 to 50 ha in size and are delineated based on common site characteristics (e.g., soil, topography, and climate), vegetation types, and management history. Most stand scale treatments are designed to reduce the potential for large crown fires (Agee and Skinner 2005). To meet this broad intent, stand scale fuel treatments focus on altering multiple elements of forest structure to meet three common objectives (Keyes and O'Hara 2002; Agee and Skinner 2005; Jain et al. 2012). The first two objectives suggest that fuel treatments should reduce or limit the initiation of crown fire activity and the spread of fire through the canopy. The third objective seeks to promote forest resiliency through the maintenance of large diameter dominant fire-resistant trees. This objective is commonly applied in ecosystems where the dominant vegetation has developed a resistance to low-intensity wildland fires (e.g., ponderosa pine, Jeffrey pine, or longleaf pine ecosystems); however, it may not be an important objective in ecosystems which are dominated by species that are not resistant to low-intensity surface fires or which have regeneration strategies to deal with high-intensity crown fires. Because the inclusion of objective three into fuel treatment design is ecosystem dependent, we do not discuss it further. The first two objectives are often accomplished by designing treatments that reduce surface and canopy fuel load and increase the canopy base height (i.e., the distance or gap between the surface and canopy fuel). Conceptually reductions in surface fuel load and increased canopy base height work in concert with each other to limit the ability of surface fires to transition into the canopy, while reductions in canopy fuel load are intended to limit the potential for crown fire spread. Treatment prescriptions commonly express the desired conditions as the residual basal area, tree density, crown spacing, canopy base height, canopy cover, species composition, and surface fuel loading.

Stand Scale Wildland Fuel Treatment Effectiveness

A variety of direct and indirect approaches have been utilized to assess fuel treatment effectiveness (Hudak et al. 2011; Safford et al. 2012; Collins et al. 2007; Stevens-Rumann et al. 2013; Kennedy and Johnson 2014; Kalies and Kent 2016). Indirect assessments of fuel treatment effectiveness typically rely on evaluating changes in the fuel complex and/or utilizing fuel data of the pre- and posttreatment stand conditions to populate wildland fire behavior models and compare the differences in predicted fire behavior. Assessments based on comparisons of pre- and posttreatment fuel complex typically focus on comparing changes in the surface fuel load, canopy base height and canopy fuel load, or canopy bulk density. Generally, changes in the surface fuel load following treatment are reduced compared to pretreatment in prescribed burn only treatment types, while mechanical only treatment types tended to increase surface fuel load relative to pretreatment conditions (Schwilk et al. 2009; Fule et al. 2012; McIver et al. 2013). This is especially evident when techniques such as mastication (Kane et al. 2009; Battaglia et al. 2010; Jain et al. 2012; Kreye et al. 2014) and lop and scatter (Graham et al. 2009; Schwilk et al. 2009;

Jain et al. 2012) are used. Treatments that used a combination of fire and mechanical approaches tend to show little change in surface fuel load relative to the pretreatment conditions. All treatment types generally result in reductions in the canopy fuel load and increase canopy base height (Fule et al. 2012; Jain et al. 2012; Safford et al. 2012; McIver et al. 2013). Reductions in canopy fuel load following treatment are positively related to treatment intensity; therefore treatments that combine mechanical and burning techniques generally have the greatest effect (Fule et al. 2012). Taken as a whole, changes in the fuel complex following treatments are suggestive of reductions in the potential for crown fire activity.

A number of other studies have utilized pre- and posttreatment fuel data to populate wildland fire behavior models and then compare the simulated data to assess the effects of treatments on potential fire behavior (Fulé et al. 2004; Agee and Lolley 2006; Battaglia et al. 2008; Stephens et al. 2009; Jain et al. 2012; Ziegler et al. 2017). A number of fire behavior metrics have been utilized to assess fuel treatment effectiveness including fire rate of spread, fireline intensity, flame length, canopy consumption, and fire type. Two of the more widely assessed indices are the torching and crowning indices. These indices are estimated as the 10-m open wind speed required for transition of a surface fire into the canopy and the 10-m open wind speed required to maintain active crown fire spread, respectively (Scott and Reinhardt 2001). Comparisons between predicted fire behavior in pre- and posttreated stands indicate a consistent and significant positive effect of treatments on the crowning and torching indices as well as decreases in fireline intensities, rates of spread, and canopy consumption, providing support to the idea that treatments are effective (Fule et al. 2012). Unlike indirect assessments based on changes in the fuel complex, fire behavior modeling assessments have not consistently shown differences in effectiveness among treatment types (Fule et al. 2012). Although modeling-based assessments have consistently suggested that fuel treatments are effective, there are a number of uncertainties, potential biases, and unsupported assumptions that may limit their usefulness (Keyes and Varner 2006; Varner and Keyes 2009; Cruz et al. 2014). Despite the potential limitations of modeling-based assessments, these approaches have been critical to establish a basis for treatment effectiveness and represent the best available science (Martinson and Omi 2003), and therefore the results can be useful for relative comparisons between treatments (Fule et al. 2012).

Although the use of indirect assessments is more common than direct assessments (Martinson and Omi 2008; Fule et al. 2012), they have been utilized in a number of fuel treatment assessments (Martinson and Omi 2008; Graham et al. 2012; Hudak et al. 2011; Safford et al. 2012; Kennedy and Johnson 2014; Waltz et al. 2014). Unlike modeling-based assessments which focus on fire behavior metrics, most direct assessments have quantified changes in fire severity (e.g., tree mortality or crown scorch). These assessments have indicated that treatments are effective at reducing fire severity relative to untreated areas (Safford et al. 2012; Stevens-Rumann et al. 2013; Waltz et al. 2014); however they have also suggested that there may be trade-offs among treatment types. Similar to indirect fuel assessment techniques, direct assessments have generally suggested that treatments which combine mechanical and prescribed fire result in the greater reduction in fire severity relative to either mechanical only treatments, fire only treatments, and untreated areas (Graham et al. 2009, 2012). Direct assessments have also highlighted the importance of treatment size and spatial context in fuel treatment design (Ritchie et al. 2007; Safford et al. 2009, 2012; Kennedy and Johnson 2014).

Both direct and indirect assessments suggest that when stand wildland fuel treatments are implemented they are generally successful in meeting the short-term goals of reducing the potential for high-intensity crown fires. However, previous research does suggest that there are trade-offs among the various treatment types. Treatments that implement a combination of prescribed or managed fire along with mechanical methods are most effective at reducing the potential for crown fire initiation and spread (Schwilk et al.

2009; Prichard et al. 2010; Safford et al. 2012). The use of prescribed or managed fire alone has been found to be effective at reducing the potential for crown fire initiation but may not be as effective at reducing the potential for crown fire spread if canopy fuel loads are not reduced. Although previous research generally suggests that mechanical only treatments are effective, these results are more variable. This variability is thought to be related to the posttreatment surface fuel load and as such mechanical systems that purposefully remove or harvest the residual biomass from thinning would be expected to have better performance than those that do not (Safford et al. 2009; Prichard et al. 2010; Graham et al. 2012).

Landscape Scale Fuel Treatment Design and Efficacy

Although silvicultural activities are conventionally implemented at the scale of individual forest stands, the overall extent and the size of severely burned patches within wildfires often warrant a fuel treatment approach that extends well beyond individual forest stands to landscapes (Collins et al. 2013). In this context the term landscape captures a large contiguous area that is typically bounded by some significant break in fuel continuity (e.g., rocky ridgetops) or change in vegetation type. Often a landscape can include one to several watersheds, ranging in size from thousands to tens of thousands of hectares. Because implementing fuel treatments across an entire landscape is not feasible due to a variety of operational, economic, social, and policy constraints, land managers and scientists have recognized the need to strategically arrange a network of treated stands in such a way as to reduce the fire spread and intensity across the entire area (Finney 2001).

Landscape fuel treatment design requires an understanding of dominant fire weather patterns and likely fire behavior for a given area. This understanding can be derived from observation and local knowledge or from a suite of spatial data layers and modeling tools. Recent studies in Oregon and Northern California suggest that both approaches can be quite effective at reducing modeled landscape-level fire behavior (e.g., Ager et al. 2013; Dow et al. 2016). However, there are several factors that impact the effectiveness of a landscape fuel treatment project. Proportion of area treated is one of the primary factors. Some studies have reported reductions in modeled fire size, flame length, and spread rate with as little as 10% of the landscape treated (Ager et al. 2007; Schmidt et al. 2008). However, it appears that 20–30% treated may be a more consistent and reliable treatment level for reducing landscape-level fire spread and intensity (Finney et al. 2007). The placement of treatments or arrangement across a landscape is another important factor that influences effectiveness. Modeling studies (e.g., Finney et al. 2007) have shown that random treatment placement is substantially less effective than an informed arrangement which (1) targets "hotspots" for fire spread, (2) "layers" treatments orthogonal to the dominant fire spread direction, and (3) contains large enough individual treatment units such that the treated areas are not overwhelmed by a fast-spreading wildfire. While these criteria for effective landscape treatment design are largely untested in actual wildfires (not modeled), multiple studies have demonstrated that even in extreme wildfire events, fuel treatments can result in landscape-level reductions in fire severity (Prichard and Kennedy 2014; Lydersen et al. 2017).

In designing landscape-level fuel treatment projects, forest managers must balance potential impacts of the implementing treatments versus the expected effects of wildfire in the absence of treatments. One of the primary concerns regarding impacts of treatments themselves is the reduction in habitat quality associated with reducing surface, ladder, and canopy fuels. These concerns are particularly important when managing areas where species that prefer multistoried forest stands with closed canopies for nesting or denning habitat such as the spotted owl [*Strix occidentalis*] and Pacific fisher [*Martes pennanti*]) are present. On federally managed lands, it is common to identify "core" areas around known nesting or denning sites for these species and restrict silvicultural activities within them. In landscapes with relatively high proportions of these "core" areas, landscape fuel treatment design can be severely limited in terms of both proportion of area treated and placement of treatments. Consequently, these landscapes can be highly vulnerable to uncharacteristically extensive patches of tree mortality, which can have lasting negative impacts on habitat quality (e.g., Jones et al. 2016; Rockweit et al. 2017). These fires, and the potential for more in the future, are forcing an approach that explicitly evaluates both shorter-term impacts (i.e., lower-quality habitat resulting from treatment) and the potential for longer-term gains (i.e., maintaining large live trees on a landscape).

Wildland Fuel Treatment Maintenance and Longevity

While there is clear evidence that fuel treatments can be effective at reducing the behavior of future fires, it is critical that the transient nature of these effects is recognized (Reinhardt et al. 2008). Three major elements to consider for treatment longevity include the rate of fuel decay, fuel growth, and fuel recruitment (Jain et al. 2012). Due to the dynamic nature of forests (i.e., growth and mortality), fuel treatments have a "lifespan," after which follow-up treatments need to be conducted to reduce accumulated fuel. Accumulated fuel can be in the form of leaf and branch deposition from residual trees, as well as regenerating trees and shrubs that establish after treatment. The rate of fuel accumulation is a key factor that affects treatment longevity. Accumulation rates are influenced by the type and intensity of treatment, site productivity, and understory vegetation responses. For example, mechanical treatments that only target removal of ladder and crown fuels would not be expected to have as much longevity as a mechanical treatment followed by prescribed fire, which effectively reduces ladder, crown, and surface fuels (Stephens et al. 2012). However, it is worth considering the potential stimulating effect that fire treatments can have on the development of live surface fuels (shrub and tree regeneration), due to increased mineral soil exposure and seed scarification (Collins et al. 2007). Both modeling and empirical studies suggest that treatments can be expected to reduce fire behavior for 10–20 years (Battaglia et al. 2008; Collins et al. 2011; Tinkham et al. 2016). Given that capacity for planning and implementing treatments is not unlimited, there is an inherent trade-off between expanding the footprint of treated area across landscapes and performing maintenance on existing treatments. One approach that has been proposed for addressing the balance between maintaining existing treatments versus expanding the overall treatment footprint has been to use fire (both prescribed fire and managed wildfire) under moderate weather conditions following the implementation of a landscape fuel treatment project (North et al. 2012). This approach would be most appropriate for forest types that were historically adapted to frequent fire.

Summary

Wildland fuel treatments are a key land management tool to reduce the potential negative effects of wildfires. By using either mechanical methods, managed wildfire, or both, research has shown that modifying the fuel complex can modify fire behavior and minimize undesired wildfire impacts. Design of fuel treatments should consider the importance of placement on the landscape as well as creating treatments of sufficient size to modify landscape-level fire. Since forests are dynamic and continue to grow and accumulate fuels, the effectiveness of fuel treatments is transient, requiring follow-up maintenance treatments.

Cross-References

▶ Active Crown Fire
▶ Crown Fire
▶ Fuel Characterization
▶ Masticated Fuels
▶ Passive Crown Fire
▶ Surface to Crown transition
▶ WUI Fuel Treatments

References

Agee JK, Lolley MR (2006) Thinning and prescribed fire effects on fuels and potential fire behavior in an eastern Cascades forest, Washington, USA. Fire Ecol 2:3–19

Agee JK, Skinner CN (2005) Basic principles of forest fuel reduction treatments. Forest Ecol Manag 211: 83–96

Ager AA, Finney MA, Kerns BK, Maffei H (2007) Modeling wildfire risk to northern spotted owl (Strix occidentalis caurina) habitat in Central Oregon, USA. Forest Ecol Manag 246:45–56

Ager AA, Vaillant NM, McMahan A (2013) Restoration of fire in managed forests: a model to prioritize landscapes and analyze tradeoffs. Ecosphere 4: 1–19

Battaglia MA, Smith FW, Shepperd WD (2008) Can prescribed fire be used to maintain fuel treatment effectiveness over time in Black Hills ponderosa pine forests? Forest Ecol Mana 256:2029–2038

Battaglia MA, Rocca ME, Rhoades CC, Ryan MG (2010) Surface fuel loadings within mulching treatments in Colorado coniferous forests. For Ecol Manag 260:1557–1566

Brown JK, Smith JK (2000) Wildland fire in ecosystems: effects of fire on flora, Gen. Tech. Rep. RMRS-GTR-42, vol 2. USDA Forest Service, Rocky Mountain Research Station, Ogden

Collins BM, Moghaddas JJ, Stephens SL (2007) Initial changes in forest structure and understory plant communities following fuel reduction activities in a Sierra Nevada mixed conifer forest. Forest Ecol Manag 239:102–111

Collins BM, Stephens SL, Roller GB, Battles JJ (2011) Simulating fire and forest dynamics for a landscape fuel treatment project in the Sierra Nevada. For Sci 57: 77–88

Collins BM, Kramer HA, Menning K, Dillingham C, Saah D, Stine PA, Stephens SL (2013) Modeling hazardous fire potential within a completed fuel treatment network in the northern Sierra Nevada. Forest Ecol Manag 310:156–166

Covington WW, Moore MM (1994) Southwestern ponderosa forest structure: changes since Euro-American settlement. J Forest 92:39–47

Covington WW, Fule PZ, Hart SC, Kolb TE, Mast JN, Sackett SS, Wagenr MR (1997) Restoration of ecosystem health in southwestern ponderosa pine forests. J Forest 95:23–29

Cruz MG, Alexander ME, Dam JE (2014) Using modeled surface and crown fire behavior characteristics to evaluate fuel treatment effectiveness: a caution. For Sci 60:1000–1004

Dow CB, Collins BM, Stephens SL (2016) Incorporating resource protection constraints in an analysis of landscape fuel treatment effectiveness in the northern Sierra Nevada, CA, USA. Environ Manag 57:516–530

Finney MA (2001) Design of regular landscape fuel treatment patterns for modifying fire growth and behavior. For Sci 47:219–228

Finney MA, Seli RC, McHugh CW, Ager AA, Bahro B, Agee JK (2007) Simulation of long-term landscape-level fuel treatment effects on large wildfires. Int J Wildland Fire 16:712–727

Flannigan MD, Krawchuk MA, de Groot WJ, Wotton BM, Gowman LM (2009) Implications of changing climate for global wildland fire. Int J Wildland Fire 18:483–507

Fry DL, Stephens SL (2006) Influence of humans and climate on the fire history of a ponderosa pine-mixed conifer forest in the southeastern Klamath Mountains, California. Forest Ecol Manag 223:428–438

Fulé PZ, Crouse JE, Cocke AE, Moore MM, Covington WW (2004) Changes in canopy fuels and potential fire behavior 1880–2040: Grand Canyon, Arizona. Ecol Model 175:231–248

Fule PZ, Crouse JE, Roccaforte JP, Kalies EL (2012) Do thinning and/or burning treatments in western USA ponderosa or Jeffrey pine-dominated forests help restore natural fire behavior. Forest Ecol Manag 269: 68–81

Graham RT, Jain TB, Loseke M (2009) Fuel treatments, fire suppression, and their interaction with wildfire and its impacts: the warm Lake experience during the Cascade complex of wildfires in central Idaho, 2007, Gen. Tech. Rep. RMRS-GTR-229. USDA, Forest Service, Rocky Mountain Research Station, Fort Collins

Graham R, Finney M, McHugh C, Cohen J, Calkin D, Stratton R, Bradshaw L, Nikolov N (2012) Fourmile canyon fire findings, Gen. Tech. Rep. RMRS-GTR-289. USDA, Forest Service, Rocky Mountain Research Station, Fort Collins

Hessburg PF, Agee JK, Franklin JF (2005) Dry forests and wildland fires of the inland Northwest USA: contrasting the landscape ecology of the pre-settlement and modern eras. Forest Ecol Manag 211:117–139

Hudak AT, Rickert I, Morgan P, Strand E, Lewis SA, Robichaud P, Hoffman CM, Holden ZA (2011) Review of fuel treatment effectiveness in forests and rangelands and a case study from the 2007 megafires in central Idaho USA, Gen. Tech. Rep. RMRS-GTR-252. USDA Forest Service, Rocky Mountain Research Station, Fort Collins

Jain TB, Battaglia MA, Han HS, Graham RT, Keyes CR, Fried JS, Sandquist JE (2012) A comprehensive guide to fuel management practices for dry mixed conifer forests in the northwestern United States, Gen. Tech. Rep. RMRS-GTR-292. USDA, Forest Service, Rocky Mountain Research Station, Fort Collins

Jones GM, Gutiérrez RJ, Tempel DJ, Whitmore SA, Berigan WJ, Peery MZ (2016) Megafires: an emerging threat to old-forest species. Front Ecol Environ 14: 300–306

Kalies EL, Kent LLY (2016) Tamm review: are fuel treatments effective at achieving ecological and social objectives? A systematic review. Forest Ecol Manag 375:84–95

Kane JM, Varner JM, Knapp EE (2009) Novel fuelbed characteristics associated with mechanical mastication treatments in northern California and south-western Oregon. USA Int J Wildland Fire 18:686–697

Keeley JE, Bond WJ, Bradstock RA, Pausas JG, Rundel PW (2011) Fire in Mediterranean ecosystems: ecology, evolution and management. Cambridge University Press, Cambridge, UK

Kennedy MC, Johnson MC (2014) Fuel treatment prescriptions alter spatial patterns of fire severity around the wildland–urban interface during the Wallow Fire, Arizona, USA. Forest Ecol Manag 318:122–132

Keyes CR, O'Hara KL (2002) Quantifying stand targets for silvicultural prevention of crown fires. Western J Appl For 17:101–109

Keyes CR, Varner JM (2006) Pitfalls in the silvicultural treatment of canopy fuels. Fire Management Today 66: 46–50

Kreye JK, Brewer NW, Morgan P, Varner JM, Smith AM, Hoffman CM, Ottmar RD (2014) Fire behavior in masticated fuels: a review. Forest Ecol Manag 314:193–207

Lydersen JM, Collins BM, Brooks ML, Matchett JR, Shive KL, Povak NA, Kane VR, Smith DF (2017) Evidence of fuels management and fire weather influencing fire severity in an extreme fire event. Ecoll Apps 27:2013–2030

Martinson EJ, Omi PN (2003) Performance of fuel treatments subjected to wildfires. In: Omi PN, Joyce LA (eds) Fire, fuel treatments, and ecological restoration: conference proceedings; 2002 16–18 April; Fort Collins, CO. RMRS-P-29. USDA Forest Service, Rocky Mountain Research Station, Fort Collins

Martinson EJ, Omi PN (2008) Assessing mitigation of wildfire severity by fuel treatments–an example from the Coastal Plain of Mississippi. Int J Wildland Fire 17:415–420

McIver JD, Stephens SL, Agee JK, Barbour J, Boerner RE, Edminster CB, Erickson KL, Farris KL, Fettig CJ, Fiedler CE, Haase S (2013) Ecological effects of alternative fuel-reduction treatments: highlights of the National Fire and Fire Surrogate study (FFS). Int J Wildland Fire 22:63–82

North M, Collins BM, Stephens S (2012) Using fire to increase the scale, benefits, and future maintenance of fuels treatments. J Forest 110:392–401

Prichard SJ, Kennedy MC (2014) Fuel treatments and landform modify landscape patterns of burn severity in an extreme fire event. Ecol Apps 24:571–590

Prichard SJ, Peterson DL, Jacobson K (2010) Fuel treatments reduce the severity of wildfire effects in dry mixed conifer forest, Washington, USA. Can J For Res 40:1615–1626

Reinhardt ED, Keane RE, Calkin DE, Cohen JD (2008) Objectives and considerations for wildland fuel treatment in forested ecosystems of the interior western United States. Forest Ecol Manag 256:1997–2006

Ritchie MW, Skinner CN, Hamilton TA (2007) Probability of tree survival after wildfire in an interior pine forest of northern California: effects of thinning and prescribed fire. For Ecol Manag 247:200–208

Rockweit JT, Franklin AB, Carlson PC (2017) Differential impacts of wildfire on the population dynamics of an old-forest species. Ecology 98:1574–1582

Safford HD, Schmidt DA, Carlson CH (2009) Effects of fuel treatments on fire severity in an area of wildland–urban interface, Angora Fire, Lake Tahoe Basin, California. Forest Ecol Manag 258:773–787

Safford HD, Stevens JT, Merriam K, Meyer MD, Latimer AM (2012) Fuel treatment effectiveness in California yellow pine and mixed conifer forests. Forest Ecol Manag 274:17–28

Schelhaas MJ, Nabuurs GJ, Schuck A (2003) Natural disturbances in the European forests in the 19th and 20th centuries. Glob Chang Biol 9:1620–1633

Schmidt DA, Taylor AH, Skinner CN (2008) The influence of fuels treatment and landscape arrangement on simulated fire behavior, Southern Cascade range, California. Forest Ecol Manag 255:3170–3184

Schwilk DW, Keeley JE, Knapp EE, McIver J, Bailey JD, Fettig CJ, Fiedler CE, Harrod RJ, Moghaddas JJ, Outcalt KW, Skinner CN (2009) The national fire and fire surrogate study: effects of fuel reduction methods on forest vegetation structure and fuels. Ecol Apps 19:285–304

Scott JH, Reinhardt ED (2001) Assessing crown fire potential by linking models of surface and crown fire behavior, Res. Pap. RMRS-RP-29. USDA, Forest Service, Rocky Mountain Research Station, Fort Collins

Stephens SL, Fulé PZ (2005) Western pine forests with continuing frequent fire regimes: possible reference sites for management. J Forest 103:357–362

Stephens SL, Moghaddas JJ, Edminster C, Fiedler CE, Haase S, Harrington M, Keeley JE, Knapp EE, McIver JD, Metlen K, Skinner CN (2009) Fire treatment effects on vegetation structure, fuels, and potential fire severity in western US forests. Ecol Apps 19:305–320

Stephens SL, Collins BM, Roller GB (2012) Fuel treatment longevity in a Sierra Nevada mixed conifer forest. Forest Ecol Manag 285:204–212

Stevens-Rumann C, Shive K, Fule PZ, Sieg CH (2013) Pre-wildfire fuel reduction treatments result in more resilient forest structure a decade after wildfire. Int J Wildland Fire 22:1108–1117

Tinkham WT, Hoffman CM, Ex SA, Battaglia MA, Saralecos JD (2016) Ponderosa pine forest restoration treatment longevity: implications of regeneration on fire hazard. Forests 7:137

Varner JM, Keyes CR (2009) Fuels treatments and fire models: errors and corrections. Fire Manag Today 69:47–50

Waltz AE, Stoddard MT, Kalies EL, Springer JD, Huffman DW, Meador AS (2014) Effectiveness of fuel reduction treatments: assessing metrics of forest resiliency and wildfire severity after the Wallow Fire, AZ. Forest Ecol Manag 334:43–52

Ziegler JP, Hoffman CM, Battaglia M, Mell W (2017) Spatially explicit measurements of forest structure and fire behavior following restoration treatments in dry forests. Forest Ecol Manag 386:1–12