

Using Fire to Increase the Scale, Benefits, and Future Maintenance of Fuels Treatments

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The USDA Forest Service is implementing a new planning rule and starting to revise forest plans for many of the 155 National Forests. In forests that historically had frequent fire regimes, the scale of current fuels reduction treatments has often been too limited to affect fire severity and the Forest Service has predominantly focused on suppression. In addition to continued treatment of the wildland urban interface, increasing the scale of low- and moderate-severity fire would have substantial ecological and economic benefits if implemented soon. We suggest National Forests identify large contiguous areas to concentrate their fuels reduction efforts, and then turn treated firesheds over to prescribed and managed wildfire for future maintenance. A new round of forest planning provides an opportunity to identify and overcome some of the current cultural, regulatory, and institutional barriers to increased fire use that we discuss.

Keywords: fire policy, fire suppression, forest restoration, Forest Service planning rule, managed wildfire, Sierra Nevada

The USDA Forest Service (2012a) has adopted a new planning rule and is beginning to revise forest plans for most of the National Forests, many of which are operating under 20–30 yr old plans. The planning rule directs responsible officials to “consider opportunities to restore fire adapted ecosystems and for landscape scale restoration” (Federal Register 77(68): 21174). Three of the eight forests nationally that will lead with plan revisions under this new rule are in California’s Sierra Nevada (Sierra, Sequoia, and Inyo National Forests). In these forests, as in much of the western United States, fuels reduction has been a priority as the size and severity of wildfires

has been increasing (Miller et al. 2009). However, both the scale and implementation rate for fuel treatment projects is well behind what is necessary to make a meaningful difference across landscapes (USDA Forest Service 2011). This issue is particularly relevant as wildfire size and intensity are projected to increase in many parts of the Sierra Nevada based on climate modeling (Lenihan et al. 2008, Westerling et al. 2011). It is almost an axiom in California forest management that given many existing restrictions, prescribed and managed wildfires will never be practical on a large scale for fuels reduction treatments (Quinn-Davidson and Varner 2011). California has some of the

most restrictive air quality regulations in the country, a relatively high density of rural homes surrounded by flammable vegetation, extremely dry conditions during periods when prescribed fire could be used, and rugged topography that challenges containment efforts. Prescribed and managed wildfire do not generate revenue and therefore cannot cover management expenses, and managers may be liable if a fire escapes containment and damages property or inflicts injury. All of these concerns contribute to the general underuse of fire as a tool for both fuels reduction and forest restoration. We believe, however, much of the current approach to managing frequent-fire forests responds disproportionately to these immediate constraints and this approach is making it more difficult to reach long-term ecological and economic goals (Collins and Stephens 2007).

In this paper, we examine why managed wildfire and prescribed fire may be a more successful means of changing the scale and benefits of fuels treatment for fire-dependent forest ecosystems. We first estimate what the historic levels of burning may have been in California’s Sierra Nevada under an active fire regime and compare this estimate to the scale of current fuels treatment efforts.

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We then discuss how ecological and economic benefits decline as fuels reduction is postponed. In an effort to overcome current constraints, we use “stretch goals” and “backcasting” (Manning et al. 2006) methods suggested by some restoration ecologists to identify a desired condition (i.e., greater fire use) and that work back to the means by which forest managers might get to this future goal. We conclude by examining some of the perceived constraints on increasing fire use and what changes may help diminish these constraints. It has been suggested that current fire policies are triage that treat the consequences of fire suppression without proactively focusing on redirecting fire to an ecologically beneficial role (Weatherspoon and Skinner 1996, Stephens and Ruth 2005). Increased prescribed burning and managed wildfire use may in part help effect some of this needed change.

In this discussion, we want to immediately make two distinctions about forest use areas and fire severity. What we focus on in this paper is the forest outside the wildland urban interface (WUI) (defined in the Federal Register as the area “where humans and their development meet or intermix with wildland fuel”). In the WUI, fire containment and suppression must be the primary goal of fuels treatments (Moghaddas and Craggs 2007). Outside the WUI, however, fuels treatments “should focus on creating conditions in which fire can occur without devastating consequences” (Reinhardt et al. 2008, p. 1998). Current policies often conflate fuels treatment with suppression or containment, when outside the WUI a more useful objective may be reducing adverse fire effects and intensity rather than occurrence and size (SNEP 1996, Stephens and Ruth 2005, Reinhardt et al. 2008). This raises the second distinction we want to emphasize. We focus on the benefits of restoring historic patterns of low- and moderate-severity fire to forests that historically had frequent fire. We are not suggesting all fire is beneficial, particularly many modern wildfires that can have large areas burned at high severity. Outside of the WUI, management that emphasizes suppression ignores the inevitable consequence that reducing burn area in the present is counter productive in the long run. Inevitably these forests burn, and the longer that fire is excluded, the greater the likelihood that fire severity will increase and have large-scale adverse impacts (Biswell 1989, Marlon et al. 2012). The current pri-

ority and pace of fuels treatments outside the WUI is unlikely to significantly influence fire intensity and severity.

Current Fuels Treatments Compared to Historic Burn Acreage

Although recreating historic fire regimes may not be practical, understanding the extent of historic fire can give some general bounds on the level of fuels reduction that Sierra Nevada forests evolved with. How much Sierra Nevada forest would the Forest Service (FS) and National Park Service (NPS) need to treat each year to maintain the level of fuels reduction that forests experienced with an active (pre-1850) fire regime? We have included the NPS to compare with the FS because of its proportionally greater use of prescribed fire and managed wildfire to achieve land management objectives.

Using a GAP analysis that identified the acreage and agency ownership of different forest types in the Sierra Nevada (Davis and Stoms 1996), we calculated how much acreage might have historically burned each year by forest type. GAP analyses are used to identify how plant communities are distributed between different ownerships and aid in identifying where there are ‘gaps’ in conserving biodiversity (Scott et al. 1993). We loosely grouped the forest types into two categories; (1) active management for those forests more often outside of wilderness on Forest Service land and in the more accessible front country in the Sierra Nevada’s two National Parks, Yosemite and Sequoia/Kings Canyon, and (2) passive management for the other forest types (Table 1). We estimated the acreage that would annually burn in each forest type using two values of historic fire return intervals (HFRI). We calculated HFRI after reviewing two published studies (Stephens et al. 2007, van de Water

and Safford 2011) that summarize information from hundreds of fire history studies, and the online fire effects information system (USDA Forest Service 2012b). We calculated the overall mean, and the mean of the highest quartile (hereafter referred to as high) of HFRI values (Table 1). We included the latter value as a very conservative estimate, one that managers might consider a minimal but approachable target given constraints on fuels reduction.

The analysis suggests the FS would need to reduce fuels annually on more than 487,000 ac/yr total (454,000 ac/yr in active management forest types) and more than 183,000 ac/yr total (171,000 ac/yr in active management forest types) using the mean and high HFRI (Table 1), respectively, to approach historic levels. The NPS would need to reduce fuels annually on more than 65,000 ac/yr total (48,000 ac/yr in active management forest types) and more than 24,000 ac/yr total (18,000 ac/yr in active management forest types) using the mean and high HFRI, respectively (Table 1). Total acreage of FS lands is approximately five times that of the NPS in the Sierra Nevada, yet it has a much higher burn acreage total because it has ten times more acreage than the NPS in the forest types that generally have low HFRI. In contrast, the FS has only twice the amount of acreage of the NPS in forest types generally at higher elevation with higher HFRI.

Current annual fuels reduction on FS land averages 87,923 ac of which 28,598 ac is mechanical (33% of the total), 8,256 ac (9%) is prescribed fire and 51,069 ac (58%) is wildfire (Table 2). Combining both National Parks, the average annual fuels reduction is 11,279 ac/yr of which 132 ac (1%) is mechanical, 2803 ac (25%) is prescribed fire, and 8,344 ac (74%) is wildfire (Table

Management and Policy Implications

With less than 20% of the Sierra Nevada’s forested landscape receiving needed fuels treatments, and the need to frequently re-treat many areas, the current pattern and scale of fuels reduction is unlikely to ever significantly advance restoration efforts. One means of changing current practices is to concentrate large-scale fuels reduction efforts and then move treated areas out of fire suppression into fire maintenance. A fundamental change in the scale and objectives of fuels treatments is needed to emphasize treating entire firesheds and restoring ecosystem processes. As fuel loads increase, rural home construction expands, and budgets decline, delays in implementation will only make it more difficult to expand the use of managed fire. Without proactively addressing some of these conditions, the status quo will relegate many ecologically important areas (including sensitive species habitat) to continued degradation from either no fire or wildfire burning at high severity.

Table 1. Forest type, total area, mean and high (mean of highest quartile) historic fire return interval (HFRI), fractional ownership, and approximate area that, on average, would have burned annually in the Sierra Nevada for the Forest Service (FS) and National Park Service (NPS) using the mean and high HFRI. The extent of the Sierra Nevada is the Jepson (Hickman 1993) definition, which is the area from the north fork of the Feather River south to Isabella Lake. Forest types are grouped into active and passive (forest types more often located in FS wilderness or NPS "back country") management.

Forest type ^b	Area (ac)	HFRI ^a		Ownership	Forest Service			Ownership	National Park Service		
		Mean (yr)	High (yr)		Area (ac)	Mean HFRI (ac/yr)	High HFRI (ac/yr)		Area (ac)	Mean HFRI (ac/yr)	High HFRI (ac/yr)
Mix. conifer	1,466,539	12	25	0.62	909,254	75,771	36,370	0.05	73,327	6,111	2,933
West-side ponderosa	1,087,734	5	12	0.53	576,499	115,300	48,042	0.08	87,019	17,404	7,252
Lwr cismon. mix. con-oak	1,046,221	10	30	0.46	481,262	48,126	16,042	0.04	41,849	4,185	1,395
Jeff. pine-fir	730,428	8	25	0.8	584,342	73,043	23,374	0.09	65,738	8,217	2,630
Jeffrey pine	484,563	6	20	0.75	363,422	60,570	18,171	0.13	62,993	10,499	3,150
East-side ponderosa	398,819	5	15	0.76	303,103	60,621	20,207	0	0	0	0
Black oak	268,598	10	25	0.6	161,159	16,116	6,446	0.03	8,058	806	322
White fir	133,434	25	45	0.7	93,404	3,736	2,076	0.06	8,006	320	178
Aspen	24,463	30	90	0.89	21,772	726	242	0.02	489	16	5
Sequoia-mix con.	17,544	15	20	0.31	5,439	363	272	0.52	9,123	608	456
Active Man. Total	5,658,343				3,499,655	454,371	171,241		356,602	48,166	18,321
Red fir	838,905	45	90	0.61	511,732	11,372	5,686	0.3	251,671	5,593	2,796
Lodge. pine	532,748	30	110	0.6	319,649	10,655	2,906	0.42	223,754	7,458	2,034
Red fir-west. white p.	393,877	50	135	0.75	295,408	5,908	2,188	0.18	70,898	1,418	525
Whitebark p. mtn hemlock	93,404	85	180	0.62	57,910	681	322	0.37	34,559	407	192
Whitebark & lodge. pine	92,168	40	165	0.86	79,265	1,982	480	0.12	11,060	277	67
Up cismon. mix. con-oak	64,493	15	45	0.48	30,957	2,064	688	0.14	9,029	602	201
Foxtail pine	58,810	50	150	0.21	12,350	247	82	0.77	45,284	906	302
Whitebark p.	54,115	65	200	0.68	36,798	566	184	0.31	16,776	258	84
Passive Man. Total	2,128,519				1,344,068	33,475	12,536		663,031	16,918	6,201
All Man. Total	7,786,862				4,843,723	487,846	183,778		1,019,633	65,084	24,522

^a Historic fire regime interval based on all studies cited in three sources with literature reviews, Stephens et al 2007, Safford and van de Water 2012, and the fire effects information database: www.fs.fed.us/database/feis/plants/tree/.

^b Forest types based on Davis and Stoms 1996 for all forest types with > 10,000 ac.

Table 2. Average annual area and cost for mechanical treatment, prescribed fire, and wildfire control for Forest Service, Yosemite N.P. and Sequoia/Kings Canyon N.P. lands. In the area columns, numbers in parentheses are years of record and in the cost columns are the minimums to maximums reported. All cost values have been standardized to 2012 dollars. Cost ranges should be treated as rough estimates as accounting practices vary within and between agencies.

	Mechanical		Rx burn		Wildfire		Tot. area (ac)
	Area (ac)	Cost (\$/ac)	Area (ac)	Cost (\$/ac)	Area (ac)	Cost (\$/ac)	
Forest Service ^a	28,598 (2004–2011)	\$565 (\$252–1077)	8,256 (2004–2011)	\$145 (\$72–619)	51,069 (1986–2010)	\$830 (\$746–28,834 ^b)	87,923
National Park	132 (2004–2011)	N/A	2,803 (1970–2011)	\$206 ^c (\$153–458)	8,344 (1970–2011)	\$496 ^c (\$413–2,063)	11,279

^a For the Sequoia, Sierra, Stanislaus, Eldorado, Tahoe, Plumas, and Inyo National Forests and the Lake Tahoe Basin Management Unit.

^b Detailed data for 2001–2010. Cost range is lowest for the largest fire size category (>2,000 ha) and highest for the smallest category (0–0.1 ha).

^c Cost estimates only available from Sequoia/Kings Canyons N.P. For prescribed burning, the base cost is for using a N.P. crew, with costs increasing for using a contract crew. For wildfire, cost increases moving from accessible front country to backcountry wilderness.

2). Combining mechanical and prescribed fire treatments with wildfire, fuels are annually reduced on 18 or 48% (mean and high HFRI value, respectively) of the acreage that historically burned on FS land. Treatments and wildfire are reducing fuels on 17 or 46% (mean and high HFRI value, respectively) of NPS land. These estimates suggest both agencies have similar ratios of fuels reduced acreage to historic burned acreage, although by different means. For both agencies wildfire is the largest fuels reduction treatment,

but often with much different effects. With the Forest Service's priority on suppression, which has been highly effective under moderate weather conditions (Finney et al. 2007), wildfires have escaped primarily under more extreme weather conditions. FS wildfires produce a greater proportion of high severity (33%) than on NPS land (15%, data from Yosemite NP only) (Miller et al. 2009, Thode et al. 2011, Miller, J.D. 2012, unpublished data), where fires more often burn under a wider range of weather

conditions (Collins et al. 2007). Previous management practices (extensive timber harvesting, livestock grazing etc.), and a higher proportion of fuel-productive forest types may also contribute to these differences in proportions of high severity. On both FS and NPS lands, current fuels reduction acreage is substantially below historic levels, relegating most areas to accumulating high fuel loads. This increased fuel loading, however, does not necessarily produce higher fire severity if, following the NPS ex-

ample, fires are allowed to burn under moderate weather conditions.

Ecological and Economic Effects of Current FS Fuels Reduction Practices

Ironically, current FS practices intended to protect resources identified as having high ecological value often put them at a greater risk of high-severity fire. A policy focused on suppression, which ultimately results in greater wildfire intensity, means that fuels reduction becomes the principle method of locally affecting fire behavior and reducing severity (Collins et al. 2010). Forest areas identified as having high conservation value, such as riparian conservation areas (van de Water and North 2010, 2011) and protected activity centers (PAC) for threatened and sensitive wildlife (North et al. 2010) often have management restrictions and higher litigation potential, resulting in minimal or no fuels reduction treatment. Stand conditions in these protected areas often consist of multilayered canopies with large amounts of surface fuel, resulting in increased crown fire potential (Spies et al. 2006, Collins et al. 2010). Following two particularly high-intensity 2007 wildfires in the Sierra Nevada (Angora and Moonlight), riparian and PAC areas had some of the greatest percentage of high-severity effects of any area within the fire perimeters (Dailey et al. 2008, Safford et al. 2009) (Figure 1). In contrast, low- and moderate-severity wildfire and prescribed burning in Yosemite N.P. maintained habitat characteristics and density of California spotted owls (*Strix occidentalis occidentalis*) in late successional montane forest (Roberts et al. 2011) (Figure 1).

This unintended consequence of suppression-focused fire policy is not limited to forest with special designations. A particular problem in many productive, frequent-fire forests is the high duff accumulations that develop around large old trees in the absence of fuels reduction (Figure 1). Long duration smoldering burns can kill even large trees with thick bark (Ryan and Frandsen 1991, Hungerford et al. 1994). An analysis of factors associated with increased mortality found that when duff layers exceeded 5 in., the probability of mortality significantly increased, limiting conditions under which fire can burn without significant large-tree mortality (Hood 2010). The longer that fire is kept out of many productive forests, the greater the likelihood that burn intensity and duration will be higher than desired, im-



Figure 1. Top left is a California spotted owl Protected Activity Center (PAC) following the 2007 Moonlight wildfire. Top right is a Jeffrey pine with a thick duff layer accumulation around its bole in fire-suppressed mixed conifer. Bottom is a California spotted owl nest in a mixed-conifer forest that burned in a prescribed fire with mixed fire severity in 1997 in Yosemite N.P. Note the nest (shown by arrow) is in an area that burned at low severity and has high canopy closure. The nest is adjacent (<50 ft away) to an area (left one third of the photo) with lower canopy closure that experienced moderate fire severity. (Photo credit: Stephanie Eyes).

packing ecosystem services and potentially killing many of the large trees that are highly valued.

Of the three principle means of fuels reduction, mechanical, prescribed burning, and wildfire, the latter is often the most expensive in California. We surveyed Forest Service Region 5 and National Park Service personnel in Yosemite and Sequoia/Kings Canyon for cost estimate records (Table 2). [1] Costs should be treated as only general estimates because accounting practices vary within and between agencies. The general trends, however, are instructive for identifying factors that increase costs and the rough differences between different treatments. Prescribed fire tends to be the least expensive per acre with costs decreasing as the size of treated area increases. Forest Service mechanical treatments costs vary widely but costs on average were 3.5 times higher than prescribed fire in large part due to expensive service contracts for removal of small, noncommercial biomass. Wildfire costs were highest but vary tremendously between burns. In general, costs per acre increased as access became more difficult but decreased with fire size.

These estimates are fairly consistent with published studies (Rideout and Omi 1995, González-Caban 1997, Cleaves et al. 1999, Butry et al. 2001, Berry and Hesseln

2004, Berry et al. 2006, Mercer et al. 2007). In one study examining Forest Service lands burned by wildfire and their suppression costs, total costs had high annual variability correlated with total area burned, while cost per acre from 1980 on were fairly consistent at about \$760/ac (Calkin et al. 2005). In another study in southwest forests, the authors estimated that avoided future wildfire suppression costs justified spending \$271 to \$684/ac for fuels reduction (Snider et al. 2006). However, costs can vary substantially between regions. For Region 5, which includes the Sierra Nevada, wildland fire suppression costs averaged \$2,567/ac for the period of 1995–2004 (Gebert et al. 2007). Factors having the largest influence on suppression cost were fire intensity (as measured by flame length), area burned, total housing value within 20 miles of the ignition and the percent of private land within the fire perimeter (Gebert et al. 2007, Liang et al. 2008). In addition, suppression costs in Region 5 may be associated with factors related to California's population size. A recent paper suggested newspaper coverage and political pressure can substantially increase wildfire suppression costs (Donovan et al. 2010).

An additional economic consideration for the FS is that mechanical treatment costs are likely to increase. In many forests after decades of fire suppression fuels reduction

costs, particularly for service contracts, can be offset with the removal of some trees large enough to have commercial value (Hartsough 2003). Second-entry treatments for maintenance of fuels reduction will probably have higher costs when commercial size trees are rare or no longer present. With current or even shrinking FS budgets, the scale of mechanical treatments may dramatically decrease for maintenance of areas previously treated.

In the future, maintenance of existing fuels reduction treatments could eventually subsume the entire treatment effort such that some proportion of the forest is never treated and always has uncharacteristically high fuel loads (hereafter, the backlog). We roughly calculated this backlog based on some assumptions given data limitations. We assumed mechanical and prescribed fire treatment would all occur in active management forest types and be proportional to each forest type's percentage of the Forest Service's total acreage. For wildfire we used the proportions of total wildfire acreage burned by forest type during 1984–2004 (Miller et al. 2009; Table 1). Using criteria for Forest Condition Class 2 (Barrett et al. 2010), we assumed a forest would accumulate uncharacteristically high fuel loads if it were not treated within a period equal to twice the mean HFRI (Table 1) (Caprio et al. 2002). Using these proportions and current fuels reduction levels (Table 2), we calculated the total amount of acreage in each forest type that would have some form of fuels reduction (i.e., mechanical, prescribed burning, and wildfire) before treatments would have to “start over again.” We then subtracted this amount from the forest type's total acreage to calculate backlog. We estimate that at current rates the deficit of forestland “in need” of treatment would be approximately 2.9 million ac (60%) of FS acreage in the Sierra Nevada, of which 1.7 million ac (60% of the backlog) are ponderosa and Jeffrey pine dominated forest types (Figure 2). We believe this is a very conservative estimate because it assumes that mechanical, prescribed fire, and wildfire areas never overlap.

An often-cited critique of fuels treatments is that the probability of wildfire burning a treated area within the expected lifespan of the treatment is so low that treatment costs and potential impacts on forest resources (e.g., carbon, watercourses, etc.) are rarely justified (Rhodes and Baker 2008, Campbell et al. 2011). Indeed, in California

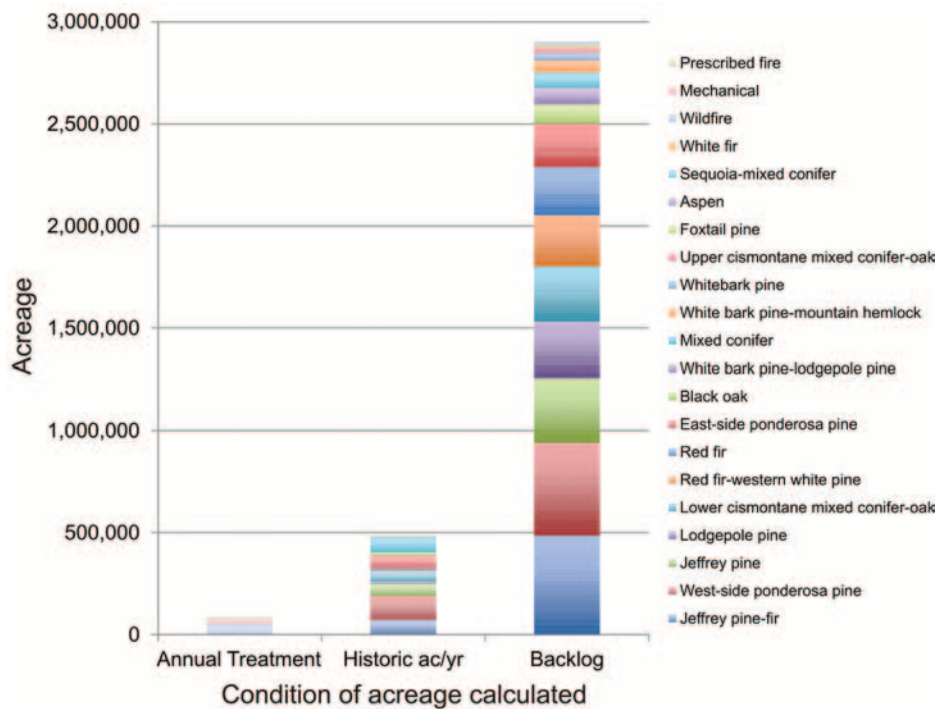


Figure 2. Histogram of the acreage of current annual fuels reduction by type, historical fuels reduction from wildfire by forest type and backlog by forest type. Backlog is a conservative estimate of the acreage that would always have uncharacteristically high fuel loads at current rates of fuels reduction and wildfire burning.

fuels treatments designed for the suppression and containment of wildfire may rarely be economical except in the WUI or areas with known high ignition probabilities (i.e., road corridors). However, the cost-benefit ratio improves if the primary goal of fuels treatment is to reduce fire severity, not size, which is most effective when treatments are arranged strategically across a landscape (Finney et al. 2007). In general managed wildfire does fuel reduction “work” at a lower cost per acre than mechanically treating or suppressing the fire. In the long-term, however, the ecological and economic benefits of managed wildfire are only realized if the burned area is removed from the land base that requires suppression and in the future is maintained by fire.

Stretch Goals and Backcasting

Collectively, current trends suggest the Forest Service needs a two- to fivefold increase in its annual fuels reduction acreage, is reducing the potential ecosystem services of untreated forest if burned by wildfire, and is engaged in a triage fuels reduction policy weighted toward suppression and high upfront, emergency costs. It is difficult to see how the pace, scale and economics of current practices can improve.

Frustrated by the ad hoc and small scale

of many restoration projects, Manning et al. (2006) suggested using stretch goals and backcasting methods to significantly increase the scale and coordination of restoration efforts for whole ecosystems. A stretch goal is when an objective cannot be achieved by incremental improvements and requires a significant change in methods. Stretch goals are ambitious long-term targets used to generate innovation for achieving outcomes that currently seem impossible (Manning et al. 2006). Backcasting is where the stretch goal's desired condition is visualized and then a pathway to that condition is worked out retrospectively. The features of problems for which backcasting is well suited are when the problem is complex, there is a need for major change and marginal changes will be insufficient to solve a problem, dominant trends are part of the problem, and time-scales are long enough to give considerable scope for deliberate choice (Dreborg 1996).

A hypothesized stretch goal for Sierra Nevada forest management is to restore as much ecologically beneficial fire into the landscape as possible (Miller et al. 2012). Using backcasting, the most practical means of getting to that desired endpoint is to significantly expand prescribed fire and managed wildfire. To meet this stretch goal we

suggest that forest plans consider a new approach in fuels reduction policy: some treatments should be scaled and located with the intent of treating an entire fireshed and then converting that area to future management and maintenance through managed wildfire and prescribed fire. A fireshed has been defined as a contiguous area with similar fire history and problem fire characteristics where a coordinated suppression effort would be most effective (Ager et al. 2006, Bahro and Perrot 2006, Anonymous 2010). In California, efforts to identify firesheds have noted, "... boundaries are also influenced by the values they contain and by fire management opportunities" (Bahro et al. 2007). The opportunity in the firesheds we propose is to identify areas where fire is not suppressed but is restored as an active ecological process. Forest plans have the opportunity to identify these areas, establish criteria for how they will be treated, and under what conditions they will be allowed to burn. This is important because most forests will need more than one treatment before their burn window can be broadened. For example, after a long hiatus fire reintroduction can leave many small dead trees, that after toppling add to surface fuel loads (Skinner 2005). In these conditions fire hazard will remain elevated until decomposition or a second treatment reduces surface fuel loads.

This approach has several economic and ecological benefits. Many FS projects are 3,000 to 8,000 ac in size, whereas firesheds in California often encompass 50,000 to 100,000 ac or more (Bahro et al. 2007). This size would have economic efficiencies by providing an opportunity to bundle revenue-generating areas with lightly treated forests such as riparian and PAC areas that are revenue sinks (Hartsough 2003). For example, the FS is currently varying fuels treatments with topography to simulate the forest structure and pattern that might have historically been produced by an active-fire regime (Skinner et al. 2006, North et al. 2009). Revenue from heavier thinning on upper slopes designed to restore low-density large pine conditions might be used to support hand thinning and/or prescribed burning that maintains higher canopy cover in the parallel track of forest in the drainage bottom (Figure 3). The larger scale of treatments and the practical need to spread them out over several years would make for a steady, more predictable flow of wood for local mills and potential biomass plants.

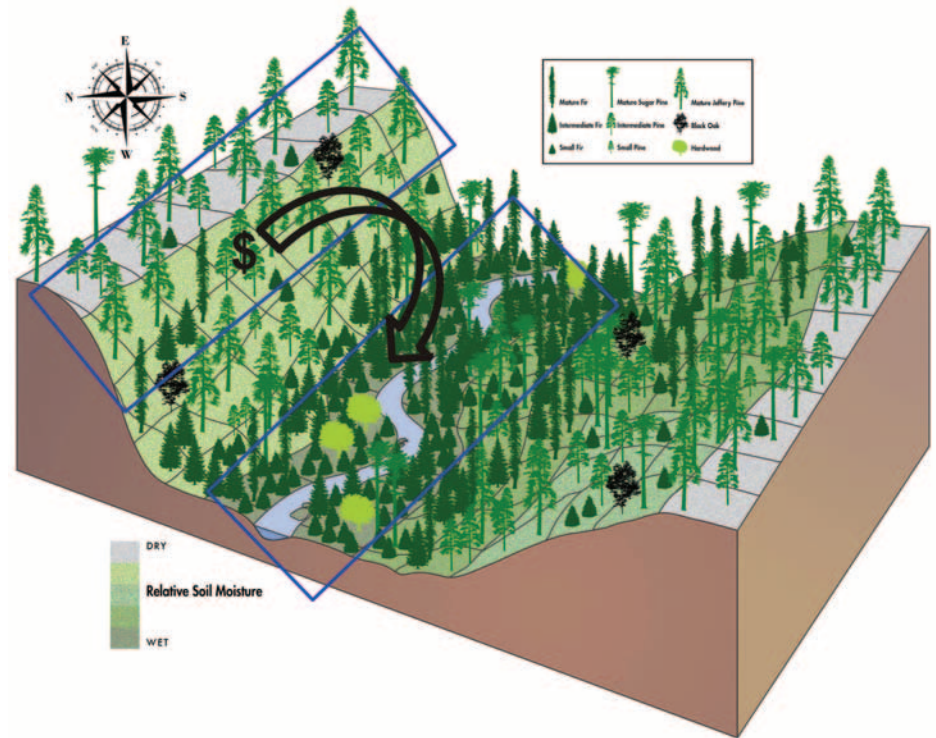


Figure 3. Example of how fuels treatments could be coupled to afford treating ecologically significant areas. The landscape schematic shows how variable forest conditions are produced by management treatments that differ by topographic factors such as slope, aspect, and slope position. Ridge tops and upper slopes have the lowest stem density and highest percentage of pine in contrast to riparian areas. Mid-slope forest density and composition varies with aspect: density and fir composition increase on more northern aspects and flatter slope angles. Revenue from heavier thinning on upper slope and ridge tops might be used to support minimal fuels treatment in riparian and PAC areas. (Figure drawn by Steve Oerding, U.C. Davis, Academic Technology Services).

Biomass use of small diameter fuels holds promise for improving the economics of fuels treatments. The lack of consistent biomass supply can limit development of processing infrastructure, however, large scale, long-term treatment planning can overcome some of these limitations (Hampton et al. 2011). Nor would this strategy just be a short-term boom, as it would take decades to widely implement fire-maintained firesheds, and once implemented there will still be a need for strategic mechanical fuels reduction. In the long run, creating burn-maintained firesheds could actually make headway in reducing the backlog of acreage needing treatment while realizing economic savings by substantially reducing future maintenance costs.

Studies of different fuels treatments across a number of forest types historically associated with frequent fire consistently show the ecological benefits of fire and its essential role in ecosystem restoration (Stephens et al. 2009, 2012). Mechanical treatment alone may be able to mimic the live-

tree structure of an active-fire forest condition (North et al. 2007), but it does not restore key ecological processes such as nutrient cycling (Wohlgemuth et al. 2006), understory (Wayman and North 2007, Webster and Halpern 2010) and microclimate (Ma et al. 2010) diversity, soil respiration patterns (Concilio et al. 2006), regeneration of fire-resistant tree species (Zald et al. 2008) or provision of habitat for some species (Hutto 1995, Saab and Powell 2005). Fire can restore some ecosystem benefits within a few applications. Forest structure (Taylor 2010) and understory conditions (Webster and Halpern 2010) may approach active fire regime conditions after two burns (or in some cases one moderate severity fire may be sufficient (Collins et al. 2011)). Recent research (Nesmith et al. 2011) also suggests that "despite restrictions" prescribed fire can produce similar patterns and effects on vegetation as low-intensity wildfire. Findings from these and other studies suggest that efforts to increase forest restoration and resilience need to incorporate fire. For

this to occur at meaningful scales managed wildfire and prescribed fire needs to be a substantial component of the management portfolio.

Constraints on Fire Use

Escaped-Fire Damage

Increased use of managed wildfire and prescribed fire is not without risk (e.g., 2012 Lower North Fork fire, Colorado; 2011 Margaret River fire, Western Australia; 2000 Cerro Grande fire, New Mexico). There are lessons, however, from these experiences that can help reduce the risk of escaped fire: (1) Prescribed fire, particularly for initial-entry burns, could be constrained to a relatively narrow set of fuel moisture and weather conditions. This would involve taking advantage of favorable conditions, whenever they occur (i.e., including nighttime and weekend opportunities). At present this can be difficult when land management agencies restrict work hours; (2) Minimize use of prescribed fire in areas surrounded by hazardous fuels. Prescribed fire units could be anchored by areas with low fire behavior potential (e.g., large rock outcrops, barren ridge tops, previous fuel treatments or wildfires). This involves developing a landscape strategy for fire use in the planning process. A new tool, the “Treatment Minimizer” in the software ArcFuels may help with this planning (Vaillant et al. in press). The stated justification for this tool is “. . . forest restoration should have the goal of creating the largest area within which fire behavior does not exceed thresholds that trigger suppression”; and (3) Burn large units (>1000 ac). There is very little to gain from burning small units relative to the risk. Revised forest plans can institute policy support for problems that will inevitably occur when fire use increases (Stephens et al. 2010).

Agency Culture

Although current policy recognizes the importance and need for managed wildfire (FWFMP 2001, USDA/USDI 2005, FWFMP 2009), studies have found very low rates of implementation. In 2004, land management agencies only let 2.7% of all lightning ignitions burn (NIFC 2006), consistent with a recent analysis in the Sierra Nevada that less than 2% of FS lands were burned under managed wildfire between 2001–2008 (Silvas-Bellanca 2011). The most significant factor associated with FS

district rangers using managed wildfire was personal commitment, while the main disincentives were negative public perception, resource availability and perceived lack of agency support (Williamson 2007). For example, in Sierra Nevada National Forests, prescribed fire in mixed-conifer forests that produces >5% mortality of large overstory trees or patches of high severity has sometimes been considered as failing to meet objectives. Studies in an upper elevation mixed-conifer forest with a restored fire regime, however, suggest patches of considerable overstory mortality (>75%) do occur even under moderate weather and generally low fuel loads (Collins and Stephens 2010). These patches, however, are generally small (<10 ac) and collectively make up a relatively small portion of the landscape (<15%). The top changes suggested by managers to increase managed wildfire were increased training and education, institutional support, management flexibility and lands identified for managed wildfire (Doane et al. 2006). Implementation of the new planning rule and development of new forest plans provides an opportunity to address these problems and foster an agency culture that supports increased fire use.

Rural House Density

The presence and density of homes near a fire affect suppression costs (Liang et al. 2008), increase liability risk (White 1991, Czech 1996), and limit management options for managed wildfire use (Arno and Brown 1991). As more homes are built in the forest, the size and extent of the WUI increases. One analysis found the WUI in the United States expanded by more than 52% from 1970 to 2000 with the greatest increases occurring in the western United States (Theobald and Romme 2007). The human population in California’s Sierra Nevada doubled between 1970 and 1990 and is projected to triple from 1990 to 2040 (Duane 1996). To date, however, much of that growth has been concentrated in areas with existing infrastructure (i.e., water and power). Some projections of future development suggest new home construction will be more dispersed given technology improvements and increased interest in living ‘off the grid’ (White et al. 2009). Maps of current housing density based on Theobald’s (2005) analysis of census data (Sierra Cascade Land Trust Council 2011) suggest unpopulated fireheds still exist in the Sierra Nevada, particularly in the northern and southern extent

of the range. Fire-use area designation will become more difficult the longer it is postponed as more development occurs.

Air Quality

In California, air quality restrictions severely limit burn opportunities. In general, prescribed fire and managed wildfire (“natural ignitions that are managed for resource benefit”) are subject to regulation by local air pollution control offices attempting to meet airshed standards under the Environmental Protection Agency’s Title 17 (unmanaged wildfire is sometimes exempted from the standards on a case-by-case basis under the category of “exceptional events”). This has resulted in Yosemite and Sequoia/Kings Canyon N.P. being fined, or having permission for other planned projects denied when they did not suppress prescribed and managed wildfire even though they occurred in areas designated for fire use. On a per acre basis, however, emissions from an “escaped,” unplanned, or high-severity wildfire can be substantially higher than occurs during managed wildfire or prescribed fire (Ahujá 2006). Fire-dependent forests will burn eventually, meaning the responsible choice is between periodic, lower concentrations of smoke in planned dispersal patterns or unplanned, heavy emissions where smoke drift and accumulation is uncontrolled. Current policy treats “unmanaged” wildfire occurrence and the resultant effects as ‘an act of God’ when human management decisions and inaction have actually contributed to conditions that support large, severe fires. Changes in policy should be considered which acknowledge the inevitability of forest fire emissions and encourage responsible management actions that minimize harmful human exposure.

Conclusion

Region 5 of the Forest Service is embarking on developing their next round of forest plans designed to set the standards and guidelines for forestry practices for the next 10–20 years. Other Forest Service regions will likely be facing similar forest plan revisions in the near future and may look to Region 5 forests for guidance under the new programmatic planning rule. With less than 20% of the landscape that needs it receiving fuels treatments, and the need to re-treat many areas every 15–30 years depending on forest type, the current pattern and scale of fuels reduction is unlikely to ever significantly advance restoration efforts, particu-

larly if agency budgets continue to decline. Treating and then moving areas out of fire suppression into fire maintenance is one means of changing current patterns. A fundamental change in the scale and objectives of fuels treatments is needed to emphasize treating entire firesheds and restoring ecosystem processes. As fuel loads increase, rural home construction expands, and budgets decline, delays in implementation will only make it more difficult to expand the use of managed fire. This approach may be criticized given current constraints but at least it could stimulate discussions between stakeholders, air quality regulators, and forest managers about current and future constraints on management options. Without proactively addressing some of these conditions, the status quo will relegate many ecologically important areas to continued degradation from fire exclusion. In some forests, revenue generated in the initial entry (Hartsough et al. 2008) may be the best opportunity to increase the scale and shift the focus of current fuels reduction toward favoring fire restoration.

Endnote

- [1] All dollar values reported in this paper have been standardized to 2012 dollars.

Literature Cited

- AGER, A.A., M.A. FINNEY, AND B. BAHRO. 2006. Automating fireshed assessments and analyzing wildfire risk with ArcFuels. *For. Ecol. Manage.* 234S:215.
- AHUJA, S. 2006. Fire and air resources. P. 444–465 in *Fire in California's Ecosystem*, Sugihara, N.G., J.W. van Wagendonk, K.E. Shaffer, J. Fites-Kaufman, and A.E. Thode (eds.). University of California Press, Berkeley, CA.
- CALIFORNIA BOARD OF FORESTRY AND FIRE PROTECTION 2010. *The 2010 strategic fire plan for California. California Board of Forestry and Fire Protection: The Strategic Fire Plan*. Available online at www.bof.fire.ca.gov/board_committees/resource_protection_committee/current_projects/resources/2010_fire_plan_1-27-10_version.pdf; last accessed Feb. 15, 2012.
- ARNO, S.F., AND J.K. BROWN. 1991. Overcoming the paradox in managing wildland fire. *West. Wildl.* 17:40–46.
- BAHRO, B., AND L. PERROT. 2006. Fireshed assessment. P. 454–456 in *Fire in California's Ecosystems*, Sugihara, N.G., J.W. van Wagendonk, K.E. Shaffer, J. Fites-Kaufman, and A.E. Thode (eds.). University of California Press, Berkeley, CA.
- BAHRO, B., K.H. BARBER, J.W. SHERLOCKS, AND D.A. YASUDA. 2007. Stewardship and fireshed assessment: a process for designing a landscape fuel treatment strategy. Pages 41–54 in *Restoring fire-adapted ecosystems: Proceedings of the 2005 National Silviculture Workshop*, R.F. Powers (tech. ed.). USDA For. Ser., Rep. No. PSW-GTR-203.
- BARRETT, S., D. HAVLINA, J. JONES, W. HANN, C. FRAME, D. HAMILTON, K. SCHON, T. DEMEO, L. HUTTER, AND J. MENAKIS. 2010. *Interagency Fire Regime Condition Class Guidebook. Version 3.0*, Homepage of the Interagency Fire Regime Condition Class website, USDA Forest Service, US Department of the Interior, and The Nature Conservancy. Available online at www.frcc.gov; last accessed Aug. 3, 2012.
- BERRY, A.H., AND H. HESSELN. 2004. The effect of the wildland-urban interface on prescribed burning costs in the Pacific Northwestern United States. *J. For.* 102:33–37.
- BERRY, A.H., G. DONOVAN, AND H. HESSELN. 2006. Prescribed burning costs and the WUI: Economic effects in the Pacific Northwest. *West. J. Appl. For.* 21:72–78.
- BISWELL, H.H. 1989. *Prescribed Burning in California Wildlands Vegetation Management*. University of California Press, Berkeley, CA. 254 p.
- BUTRY, D.T., D.E. MERCER, J.P. PRESTEMON, J.M. PYE, AND T.P. HOLMES. 2001. What is the price of catastrophic wildfire? *J. For.* 99:9–17.
- CALKIN, D.E., K.M. GEBERT, J. GRE JONES, AND R.P. NEILSON. 2005. Forest Service large fire area burned and suppression expenditure trends, 1970–2002. *J. For.* 103:179–183.
- CAMPBELL, J.L., M.E. HARMON, AND S.R. MITCHELL. 2011. Can fuel-reduction treatments really increase forest carbon storage in the western US by reducing future fire emissions? *Front. Ecol. Env.* 10:83–90.
- CAPRIO, A.C., C. CONOVER, M. KEIFER, AND P. LINEBACK. 2002. Fire management and GIS: a framework for identifying and prioritizing fire planning needs. *Ass. Fire Ecol. Misc. Publ.* 1:102–113.
- CLEAVES, D.A., T.K. HAINES, AND J. MARTINEZ. 1999. Prescribed burning costs: Trends and influences in the National Forest System. P. 277–288 in *Proc. of the Symposium on fire economics planning, and policy: Bottom lines*, A. González-Cabán and P.N. Omi (coords.). USDA For. Serv., Gen. Tech. Rep. No. PSW-GTR-173.
- COLLINS, B.M., AND S.L. STEPHENS. 2007. Managing natural wildfire in Sierra Nevada wilderness areas. *Front. Ecol. Env.* 5:523–527.
- COLLINS, B.M., M. KELLY, J.W. VAN WAGENDONK, AND S.L. STEPHENS. 2007. Spatial patterns of large natural fires in Sierra Nevada wilderness area. *Lands. Ecol.* 22:545–557.
- COLLINS, B.M., S.L. STEPHENS, J.J. MOGHADDAS, AND J. BATTLES. 2010. Challenges and approaches in planning fuel treatments across fire-excluded forested landscapes. *J. For.* 108: 24–31.
- COLLINS, B.M., AND S.L. STEPHENS 2010. Stand-replacing patches within a mixed severity fire regime: Quantitative characterization using recent fires in a long-established natural fire area. *Lands. Ecol.* 25:927–939.
- COLLINS, B.M., R.G. EVERETT, AND S.L. STEPHENS. 2011. Impacts of fire exclusion and recent managed fire on forest structure in old-growth Sierra Nevada mixed-conifer forests. *Ecosphere* 2:51.
- CONCILIO, A., S. RHU, S. MA, M. NORTH, AND J. CHEN. 2006. Soil respiration response to experimental disturbances over three years. *For. Ecol. Manage.* 228:82–90.
- CZECH, B. 1996. Challenges to establishing and implementing sound natural fire policy. *Renew. Res. J.* 14:14–19.
- DAILEY, S., J. FITES, A. REINER, AND S. MORI. 2008. *Fire behavior and effects in fuel treatments and protected habitat on the Moonlight fire*. Available online at www.fs.fed.us/adaptive_management/projects/FBAT/docs/Moonlight_Final_8_6_08.pdf; last accessed Apr. 8, 2010.
- DAVIS, F.W., AND D.M. STOMS. 1996. Sierran vegetation: A gap analysis. P. 671–690 in *Sierra Nevada Ecosystem Project: Final Report to Congress*. Vol. II., University of California, Davis, CA, Centers for Water and Wildlands Resources, Wildland Resources Center Rep. No. 37.
- DOANE, D., J. O'LAUGHLIN, P. MORGAN, AND C. MILLER. 2006. Barriers to wildland fire use: A preliminary problem analysis. *Int. J. Wildl.* 12: 36–38.
- DONOVAN, G.H., J.P. PRESTEMON, AND K. GEBERT. 2010. The effect of newspaper coverage and political pressure on wildfire suppression costs. *Soc. Nat. Resour.* 24:785–798.
- DREBORG, K.H. 1996. Essence of backcasting. *Futures*. 28:813–828.
- DUANE, T.P. 1996. Human settlement, 1850–2040. P. 235–360 in *The Sierra Nevada Ecosystem Project: Final Report to Congress*. Vol. II. Center for Water and Wildland Resources, U.C. Davis. Wildland Resources Center Rep. No. 37.
- FEDERAL WILDLAND FIRE MANAGEMENT POLICY (FWFMP). 2001. Review and update of the 1995 Federal Wildland Fire Management Policy, Various governmental agency partners, Washington, DC. 78 p.
- FEDERAL WILDLAND FIRE MANAGEMENT POLICY (FWFMP). 2009. *Guidance for implementation of federal wildland fire management policy*. Various governmental agency partners, Washington DC. 20 p.
- FINNEY, M.A., R.C. SELL, C.W. MCHUGH, A.A. AGER, B. BAHRO, AND J.K. AGEE. 2007. Simulation of long-term landscape-level fuel treatment effects on large wildfires. *Int. J. Wildland Fire*. 16:712–727.
- GEBERT, K.M., D.E. CALKIN, AND J. YODER. 2007. Estimating suppression expenditures for individual large wildland fires. *West J. Appl. For.* 22:188–196.
- GONZALEZ-CABAN, A. 1997. Managerial and institutional factors affect prescribed burning costs. *For. Sci.* 43:535–543.
- HAMPTON, H.M., S.E. SESNIE, J.D. BAILEY, AND G.B. SNIDER. 2011. Estimating regional wood supply based on stakeholder consensus for forest restoration in northern Arizona. *J. For.* 109: 15–26.
- HARTSOUGH, B. 2003. Economics of harvesting to maintain high structural diversity and resulting damage to residual trees. *West J. Appl. For.* 18:133–142.

- HARTSOUGH, B.R., S. ABRAMS, R.J. BARBOUR, E.S. DREWS, J.D. MCIVER, J.J. MOGHADDAS, D.W. SCHWILK, AND S.L. STEPHENS. 2008. The economics of alternative fuel reduction treatments in western United States dry forests: financial and policy implications from the National Fire and Fire Surrogate Study. *For. Econ. Pol.* 10:344–354.
- HICKMAN, J.C. 1993. *The Jepson Manual of Higher Plants of California*. University of California Press, Berkeley and Los Angeles, CA. 1400 p.
- HOOD, S.M. 2010. *Mitigating old tree mortality in long-unburned, fire-dependent forests: a synthesis*. USDA For. Serv. Gen. Tech. Rep. No. RMRS-GTR-238. 71 p.
- HUNGERFORD, R.D., K.C. RYAN, AND J.J. REARDON. 1994. Duff consumption: New insights from laboratory burning. P. 472–476 in *Proc. of the 12th International conference on fire and forest meteorology*, October 26–28, 1993, Jekyll Island, GA, Society of American Foresters, Bethesda, MD.
- HUTTO, R.L. 1995. The composition of bird communities following stand-replacement fires in northern Rocky Mountains (U.S.A.) conifer forests. *Conserv. Biol.* 9:1041–1058.
- LENIHAN, J.M., D. BACKELET, R.P. NEILSON, AND R. DRAPEK. 2008. Response of vegetation distribution, ecosystem productivity, and fire to climate change scenarios for California. *Clim. Change* 87:S215–S230.
- LIANG, J., D.E. CALKIN, K.M. GEBERT, T.J. VENN, AND R.P. SILVERSTEIN. 2008. Factors influencing large wildland fire suppression expenditures. *Int. J. Wildl. Fire* 17:650–659.
- MA, S., A. CONCILIO, B. OAKLEY, M. NORTH, AND J. CHEN. 2010. Spatial variability in microclimate in a mixed-conifer forest before and after thinning and burning treatments. *For. Ecol. Manage.* 259:904–915.
- MANNING, A.D., D.B. LINDENMAYER, AND J. FISHER. 2006. Stretch goals and backcasting: Approaches for overcoming barriers to large-scale ecological restoration. *Restor. Ecol.* 14: 487–492.
- MARLON, J.R., P.J. BARTLEIN, D.G. GAVIN, C.J. LONG, R.S. ANDERSON, C.E. BRILES, K.J. BROWN, D. COLOMBAROLI, D.J. HALLETT, M.J. POWER, E.A. SCHARF, AND M.K. WALSH. 2012. Long-term perspective on wildfires in the western USA. *Proc. Natl. Acad. Sci. U.S.A.* in press. doi: 10.1703/pnas.1112839109.
- MERCER, D.E., J.P. PRESTEMON, D.T. BUTRY, AND J.M. PYE. 2007. Evaluating alternative prescribed burning policies to reduce net economic damages from wildfire. *Am. J. Agric. Econ.* 89:63–77.
- MILLER, J.D., H.D. SAFFORD, M. CRIMMINS, AND A.E. THODE. 2009. Quantitative evidence for increasing forest fire severity in the Sierra Nevada and southern Cascade Mountains, California and Nevada, USA. *Ecosystems*. 12: 16–32.
- MILLER, J.D., C.N. SKINNER, H.D. SAFFORD, E.E. KNAPP, AND C.M. RAMIREZ. 2012. Trends and causes of severity, size, and number of fires in northwestern California, USA. *Ecol. Appl.* 22:184–203.
- MOGHADDAS, J.J., AND L. CRAGGS. 2007. A fuel treatment reduces fire severity and increases suppression efficiency in a mixed conifer forest. *Int. J. Wildl. Fire* 16:673–678.
- NATIONAL INTERAGENCY FIRE CENTER (NIFC). 2006. *Wildland fire statistics*. National Interagency Fire Center: Boise, ID. Available online at www.nifc.gov/fire_info/fire_stats.htm; last accessed Feb. 15, 2012.
- NESMITH, J.C.B., A.C. CAPRIO, A.H. PFAFF, T.W. MCGINNIS, AND J.E. KEELEY. 2011. A comparison of effects from prescribed fires and wildfires managed for resource objectives in Sequoia and Kings Canyon National Parks. *For. Ecol. Manage.* 261:1275–1282.
- NORTH, M., J. INNES, AND H. ZALD. 2007. Comparison of thinning and prescribed fire restoration treatments to Sierran mixed-conifer historic conditions. *Can. J. For. Res.* 37:331–342.
- NORTH, M., P. STINE, K. O'HARA, W. ZIELINSKI, AND S. STEPHENS. 2009. *An ecosystem management strategy for Sierran mixed-conifer forests*. USDA For. Serv., PSW Gen. Tech. Rep. No. PSW-GTR-220, 49 p.
- NORTH, M., P. STINE, W. ZIELINSKI, K. O'HARA, AND S. STEPHENS. 2010. Harnessing fire for wildlife. *Wildl. Prof.* 4:30–33.
- QUINN-DAVIDSON, L.N., AND J.M. VARNER. 2011. Impediments to prescribed fire across agency, landscape and manager: an example from northern California. *Int. J. Wildl. Fire* 21:210–218.
- REINHARDT, E.D., R. KEANE, D.E. CALKIN, AND J.D. COHEN. 2008. Objective and considerations for wildland fuel treatment in forested ecosystems of the interior western United States. *For. Ecol. Manage.* 256:1997–2006.
- RHODES, J.J., AND W.L. BAKER. 2008. Fire probability, fuel treatment effectiveness and ecological tradeoffs in western U.S. public forests. *Open For. Sci. J.* 1:1–7.
- RIDEOUT, D.B., AND P.N. OMI. 1995. Estimating the cost of fuels treatment. *For. Sci.* 41:664–674.
- ROBERTS, S.L., J.W. VAN WAGTENDONK, A.K. MILES, AND D.A. KELT. 2011. Effects of fire on spotted owl site occupancy in a late-successional forest. *Biol. Conserv.* 144:610–619.
- RYAN, K.C., AND W.H. FRANDSEN. 1991. Basal injury from smoldering fires in mature *Pinus ponderosa* Laws. *Int. J. Wildl. Fire* 1:107–118.
- SAAB, V.A., AND H.D.W. POWELL. 2005. Fire and avian ecology in North America: Process influencing pattern. *Stud. Avian Biol.* 30:1–13.
- SAFFORD, H.D., D.A. SCHMIDT, AND C.H. CARLSON. 2009. Effects of fuel treatments on fire severity in an area of wildland-urban interface, Angora Fire, Lake Tahoe Basin, California. *For. Ecol. Manage.* 258:773–787.
- SCOTT, J.M., F. DAVIS, B. CSUTI, R. HOSS, B. BUTTERFIELD, C. GROVES, H. ANDERSON, S. CAICCO, F. D'ERCHIA, T.C. EDWARDS JR., J. ULLIMAN, AND R.G. WRIGHT. 1993. Gap analysis: a geographic approach to protection of biological diversity. *Wildl. Mono.* 123:1–41.
- SIERRA CASCADE LAND TRUST COUNCIL. 2011. *Foothills Area Conservation Report*. Available online at www.sierrascadelandtrustcouncil.org/foothills-area-conservation-report/; last accessed Aug. 3, 2012.
- SIERRA NEVADA ECOSYSTEM PROJECT (SNEP). 1996. *Sierra Nevada Ecosystem Project, Final Report to Congress*, Vol. I–IV. Centers for Water and Wildland Resources, University of California, Davis, CA.
- SILVAS-BELLANCA, K. 2011. *Ecological burning in the Sierra Nevada: Actions to achieve restoration*. White paper of The Sierra Forest Legacy. Available online at www.sierraforestlegacy.org/; last accessed Feb. 24, 2012.
- SKINNER, C.N. 2005. Reintroducing fire into the Blacks Mountain Research Natural Area: effects on fire hazard. P. 245–257 in *Proc. of the Symposium on ponderosa pine: Issues, trends, and management*. Ritchie, M.W., D.A. Maguire, and A. Youngblood (eds.). USDA For. Serv. Gen. Tech. Rep. No. PSW-GTR-198.
- SKINNER, C.N., A.H. TAYLOR, AND J.K. AGEE. 2006. Klamath Mountains bioregion. P. 170–194 in *Fire in California ecosystems*, Sugihara N.S., J.W. van Wagtendonk, J. Fites-Kaufmann, K. Shaffer, and A. Thode (eds.). University of California Press, Berkeley, CA.
- SNIDER, G., P.J. DAUGHERTY, AND D. WOOD. 2006. The irrationality of continued fire suppression: An avoided cost analysis of fire hazard reduction treatments versus no treatment. *J. For.* 104:431–437.
- SPIES, T.A., M.A. HEMSTROM, A. YOUNGBLOOD, AND S. HUMMEL. 2006. Conserving old-growth forest diversity in disturbance-prone landscapes. *Conserv. Biol.* 20:351–362.
- STEPHENS, S.L., AND L.W. RUTH. 2005. Federal forest-fire policy in the United States. *Ecol. Appl.* 15:532–542.
- STEPHENS, S.L., R.E. MARTIN, AND N.E. CLINTON. 2007. Prehistoric fire area and emissions from California's forests, woodlands, shrublands, and grasslands. *For. Ecol. Manage.* 251: 205–216.
- STEPHENS, S.L., J.J. MOGHADDAS, C. EDMINSTER, C.E. FIEDLER, S. HAASE, M. HARRINGTON, J.E. KEELEY, E.E. KNAPP, J.D. MCIVER, K. METLEN, C.N. SKINNER, AND A. YOUNGBLOOD. 2009. Fire treatment effects on vegetation structure, and potential fire severity in western U.S. forests. *Ecol. Appl.* 19:305–320.
- STEPHENS, S.L., C.I. MILLAR, AND B.M. COLLINS. 2010. Operational approaches to managing forests of the future in Mediterranean regions within a context of changing climates. *Environ. Res. Lett.* 5:024003.
- STEPHENS, S.L., J.D. MCIVER, R.E.J. BOERNER, C.J. FETTIG, J.B. FONTAINE, B.R. HARTSOUGH, P. KENNEDY, AND D.W. SCHWILK. 2012. Effects of forest fuel reduction treatments in the United States. *BioScience* 62:549–560.
- TAYLOR, A.H. 2010. Fire disturbance and forest structure in an old-growth *Pinus ponderosa* forest, southern Cascades, USA. *J. Veg. Sci.* 21: 561–570.
- THODE, A.E., J.W. VAN WAGTENDONK, J.D. MILLER, AND J.F. QUINN. 2011. Quantifying the fire regime distributions for severity in Yosemite National Park, California, USA. *Int. J. Wildl. Fire* 20:223–239.

- THEOBALD, D.M. 2005. Landscape patterns of exurban growth in the USA from 1980 to 2020. *Ecol. Soc.* 10:32.
- THEOBALD, D.M., AND W.H. ROMME. 2007. Expansion of the US wildland-urban interface. *Lands. Urban Plann.* 83:340–354.
- USDA FOREST SERVICE. 2011. *Region Five Ecological Restoration: Leadership Intent*. USDA Forest Service, Pacific Southwest Region. 4 p.
- USDA FOREST SERVICE. 2012a. *The Forest Planning Rule*. Available online at www.fs.usda.gov/planningrule; last accessed Aug. 3, 2012.
- USDA FOREST SERVICE. 2012b. *Tree List*. Available online at www.fs.fed.us/database/feis/plants/tree/; last accessed Aug. 3, 2012.
- USDA/USDI. 2005. *Wildland Fire Use: Implementation Procedures Reference Guide*. National Wildfire Coordinating Group. National Interagency Fire Center: Boise, ID. 71 p.
- VAILLANT, N.M., A.A. AGER, J. ANDERSON, AND L. MILLER. 2012. *ArcFuels User Guide: for use with ArcGIS 9.X*. USDA For. Serv. Gen. Tech. Rep. No. PNW-GTR. 225 p.
- VAN DE WATER, K., AND M. NORTH. 2010. Fire history of coniferous riparian forests in the Sierra Nevada. *For. Ecol. Manage.* 260:384–395.
- VAN DE WATER, K., AND M. NORTH. 2011. Stand structure, fuel loads, and fire behavior in riparian and upland forests, Sierra Nevada Mountains, USA; a comparison of current and reconstructed conditions. *For. Ecol. Manage.* 262:215–228.
- VAN DE WATER, K.M., AND H.D. SAFFORD. 2011. A summary of fire frequency estimates for California vegetation before Euro-American settlement. *Fire Ecol.* 7:26–58.
- WAYMAN, R., AND M. NORTH. 2007. Initial response of a mixed-conifer understory plant community to burning and thinning restoration treatments. *For. Ecol. Manage.* 239:32–44.
- WEATHERSPOON, C.P., AND C.N. SKINNER. 1996. Landscape-level strategies for forest fuel management. P. 1471–1492 in *Sierra Nevada Ecosystem Project: Final Report to Congress*, Vol. II. Centers for Water and Wildland Resources, University of California, Davis, Wildland Resources Center Report No. 37.
- WEBSTER, K.M., AND C.B. HALPERN. 2010. Long-term vegetation responses to reintroduction and repeated use of fire in mixed-conifer forests of the Sierra Nevada. *Ecosphere* 1:27.
- WESTERLING, A.L., B.P. BRYANT, H.K. PREISLER, T.P. HOLMES, H.G. HIDALGO, T. DAS, AND S.R. SHRESTHA. 2011. Climate change and growth scenarios for California wildfire. *Clim. Change* 109: S445–S463.
- WHITE, D.H. 1991. Legal implications associated with use and control of fire as a management practice. P. 375–384 in *High intensity fire in wildlands: Management challenges and options*, S.M. Hermann (ed.). Tall Timber Fire Ecology Conference Proc. 17, May 18–21 1989, Tallahassee, FL.
- WHITE, E.M., A.T. MORZILLO, AND R.J. ALIG. 2009. Past and projected rural land conversion in the US at state, regional, and national levels. *Lands. Urban Plann.* 89:37–48.
- WILLIAMSON, M.A. 2007. Factors in United States Forest Service district rangers' decision to manage a fire for resource benefit. *Int. J. Wildl. Fire.* 16:755–762.
- WOHLGEMUTH, P.M., K. HUBBERT, AND M.J. ARBAUGH. 2006. Fire and physical environment interactions: soil, water and air. P. 75–93 in *Fire in California's ecosystem*. Sugihara, N. G., J.W. van Wagtenonk, K.E. Shaffer, J. Fites-Kaufman, and A.E. Thode (eds.). University of California Press, Berkeley, CA.
- ZALD, H., A. GRAY, M. NORTH, AND R. KERN. 2008. Initial regeneration responses to fire and thinning treatments in a Sierra Nevada mixed-conifer forest, USA. *For. Ecol. Manage.* 256: 168–179.