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Constraints on Mechanized Treatment Significantly Limit Mechanical Fuels Reduction Extent in the Sierra Nevada

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With air quality, liability, and safety concerns, prescribed burning and managed wildfire are often considered impractical treatments for extensive fuels reduction in western US forests. For California's Sierra Nevada forests, we evaluated the alternative and analyzed the amount and distribution of constraints on mechanical fuels treatments on USDA Forest Service land. With the use of current standards and guides, feedback from practicing silviculturists, and GIS databases, we developed a hierarchy of biological (i.e., nonproductive forest), legal (i.e., wilderness), operational (i.e., equipment access), and administrative (i.e., sensitive species and riparian areas) constraints. Of the Sierra Nevada Bioregion's 10.7 million acres in USDA Forest Service ownership, 58% contains productive forest and 25% is available to mechanical treatment. National forests in the southern Sierra Nevada have higher levels of constraint due to more wilderness and steeper, more remote terrain. We evaluated different levels of operational constraints and found that increasing road building and operating on steeper slopes had less effect on increasing mechanical access than removing economic considerations (i.e., accessing sites regardless of timber volume). Constraints due to sensitive species habitat and riparian areas only reduced productive forest access by 8%. We divided the Sierra Nevada Bioregion into 710 subwatersheds (mean size of 22,800 acres) with $>$25% Forest Service ownership as an approximation of a relevant management planning unit for fire or "fireshed." Only 20% of these subwatersheds had enough unconstrained acreage to effectively contain or suppress wildfire with mechanical treatment alone. Analysis suggests mechanical treatment in most subwatersheds could be more effective if it established a fuel-reduced "anchor" from which prescribed and managed fire could be strategically expanded. With potential future increases in wildfire size and severity, fire policy and forest restoration might benefit if mechanical thinning is more widely used to leverage and complement managed fire.

Keywords: forest planning, fuels management, mixed conifer, prescribed burning, wildfire

Current rates of fuels treatment on western public lands are far below what is needed to effectively influence landscape-level fire behavior or approximate historic levels of annual area burned (Stephens and Ruth 2005, North et al. 2012). Many issues contribute to this low level of implementation (e.g., limited budgets, shrinking workforce, and other factors), but a significant factor is the challenge of working in landscapes riddled with operational constraints (Collins et al. 2010). With optimal spacing, models suggest that fuels reduction can be effective for reducing fire size and severity when roughly 15–30% of the landscape has been treated (Finney 2001, 2007). In practice, however, the increasing number of rural homes (Theobald 2005, Theobald and Romme 2007), administrative boundaries that restrict management options (Lee and Irwin 2005), and economics of wood harvest and transportation (Hartsough et al. 2008) can result in a default fuels reduction strategy of treating what is left. These constraints can affect what type of treatment is practical in different areas, with treatments broadly divided into three options, mechanical thinning (including mastication), fire (prescribed burning and managed wildfire), or a combination of both (Agee and Skinner 2005). Research has suggested that greater restoration and resilience in forests that historically had low to

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moderate severity frequent fire regimes can be achieved with treatments that include fire (North et al. 2009, Fule et al. 2012, Stephens et al. 2012). Fire, however, can be difficult to use because of smoke impacts, proximate human communities, and liability and cost constraints (Quinn-Davidson and Varner 2012). This is particularly true in densely populated areas such as California, where mechanical thinning is sometimes viewed as the only realistic means of increasing the pace and scale of fuels reduction treatment (Quinn-Davidson and Varner 2012).

Mechanical treatments,[1] however, have their own set of restrictions (Reinhardt et al. 2008). This is particularly true on public lands where legal, operational, and administrative constraints can significantly restrict treatment locations and extent. For example, mechanical thinning is not allowed in wilderness and roadless areas, may not be economical or operationally feasible in remote areas with steep ground and smaller trees, and is constrained in some areas with special administrative designations, such as sensitive species activity centers and riparian forest buffers (Donovan and Brown 2005). Furthermore, the arrangement of constrained lands within potential firesheds (i.e., subwatersheds in which fire spread may be controlled at bordering ridges) (Bahro et al. 2007) also matters because it is the scale at which fuels treatments can most effectively influence fire behavior (Finney et al. 2007). For mechanical treatments to be effective, three questions need to be examined. How extensive are these constraints, which have the greatest impact on limiting treatment extent, and how do they affect the ability to successfully influence landscape-level fire effects?

To investigate these questions, we examined constraints on mechanical operability on US Department of Agriculture (USDA) Forest Service land across the Sierra Nevada Bioregion (SNBR) (Figure 1). The intent was to identify the extent to which mechanical fuel reduction treatments can be used to meet the stated objective of increasing the pace and scale of restoration within the SNBR (USDA Forest Service 2011). In particular, we asked the following questions: (1) What percentage of the total land base has mechanical constraints? (2) How do different operational constraints (i.e., slope, distance from existing road, and economics) affect the amount and distribution of mechanically treatable areas and how does this vary across national forests (NFs) with increasing topographic relief? (3) What impact do special land management restrictions such as sensitive species habitat and riparian zones have on mechanical fuels reduction? and (4) Given the spatial distribution of these constraints, how many SNBR watersheds can be effectively treated with mechanical fuels reduction alone? The Sierra Nevada may be at the forefront for evaluating how these constraints affect forest planning. The Forest Service recently adopted a new planning rule (USDA Forest Service 2012) that initiates the development of new forest plans for most of the 155 NFs. Eight NFs have been identified as "early adopters" for plan development, and three of these (the Sierra, Sequoia, and Inyo) are in the Sierra Nevada.

Methods

We examined the amount and spatial distribution of USDA Forest Service land in the SNBR in which fuels reduction using ground-based equipment is allowed and operationally feasible, considering factors such as legislative restrictions, operational limitations, and administrative constraints.[2] Our analysis used ESRI ArcGIS software and data layers developed by the USDA Forest Service Pacific Southwest Region. Our analysis included the Lake Tahoe Basin Management Unit (for simplicity hereafter grouped with the other NFs) and 9 of the 11 NFs examined in the 2013 USDA Forest Service Sierra Nevada Bioregional Assessment (Figure 1). We excluded the Klamath and Shasta-Trinity NFs because although each has area within the SNBR, they are relatively small areas in the foothills that exclude more mountainous terrain affecting constraint patterns on the other 10 NFs.

We used a hierarchy of constraints that affect mechanical operability on Forest Service land, starting with fixed limitations and moving down to constraints with more flexibility in interpretation and implementation. At the first level (L0: Biological constraint), we started with the total acres in each NF and then removed land identified as nonforest (i.e., rock, water, barren, meadow, and shrub) and with a forest cover $<10\%$ (Table 1). Then considering only productive forestland, we removed areas where mechanical equipment is not allowed (i.e., wilderness and roadless) (L1: Legal constraint).

The next two levels of constraint were based on existing standards and guidelines (USDA Forest Service 2004) and current practices (L2: Operational and L3: Administrative) (Table 1). Current practices were identified using expert opinion from one-half dozen NF silviculturists within the SNBR area. Some operational constraints are specifically identified in the standards and guidelines (i.e., mechanical equipment is generally prohibited on slopes $>35\%$ with unstable soils), but many give managers some discretion (i.e., thinning is allowed in riparian areas, but mechanical yarders cannot travel within 50–100 ft of streams). Silviculturists gave us a range of operational constraints that were affected by three factors, slope, distance from existing road, and commercial value of the accessed forest. Mechanical equipment generally is allowed on slopes of $<35\%$, whereas some equipment (i.e., self-leveling feller-bunchers) can operate more slowly and at higher cost on slopes up to 50% with suitable soils and more valuable wood. Logging on slopes of $>50\%$ re-

Management and Policy Implications

Western US efforts to increase the pace and scale of fuels treatment and forest restoration often rely on mechanical treatment because of limitations on using managed fire. We found that with only 25% of national forestland in the Sierra Nevada available to mechanical treatment, there is limited ability to affect wildfire extent and severity in many areas. Furthermore, when these mechanical constraints are grouped and examined by subwatershed, almost half of these have too little mechanically available acreage to affect potential wildfire behavior. Mechanically treatable areas are often not optimally located for containing wildfire but are well situated as anchors from which prescribed burning and managed wildfire might be expanded. Rather than primarily planning and placing mechanical treatments to contain and suppress wildfire, many treatments could be targeted to facilitate the reintroduction of beneficial fire. After adoption of a new planning rule, three of the first eight National Forests developing new Land and Resource Management Plans ("early adopters") are in the southern Sierra Nevada. Our analysis suggests that new plans consider identifying areas and weather conditions under which fire is allowed to burn. Efforts to increase the pace and scale of fuels reduction and forest restoration are unlikely to succeed without more extensive and innovative use of managed fire.

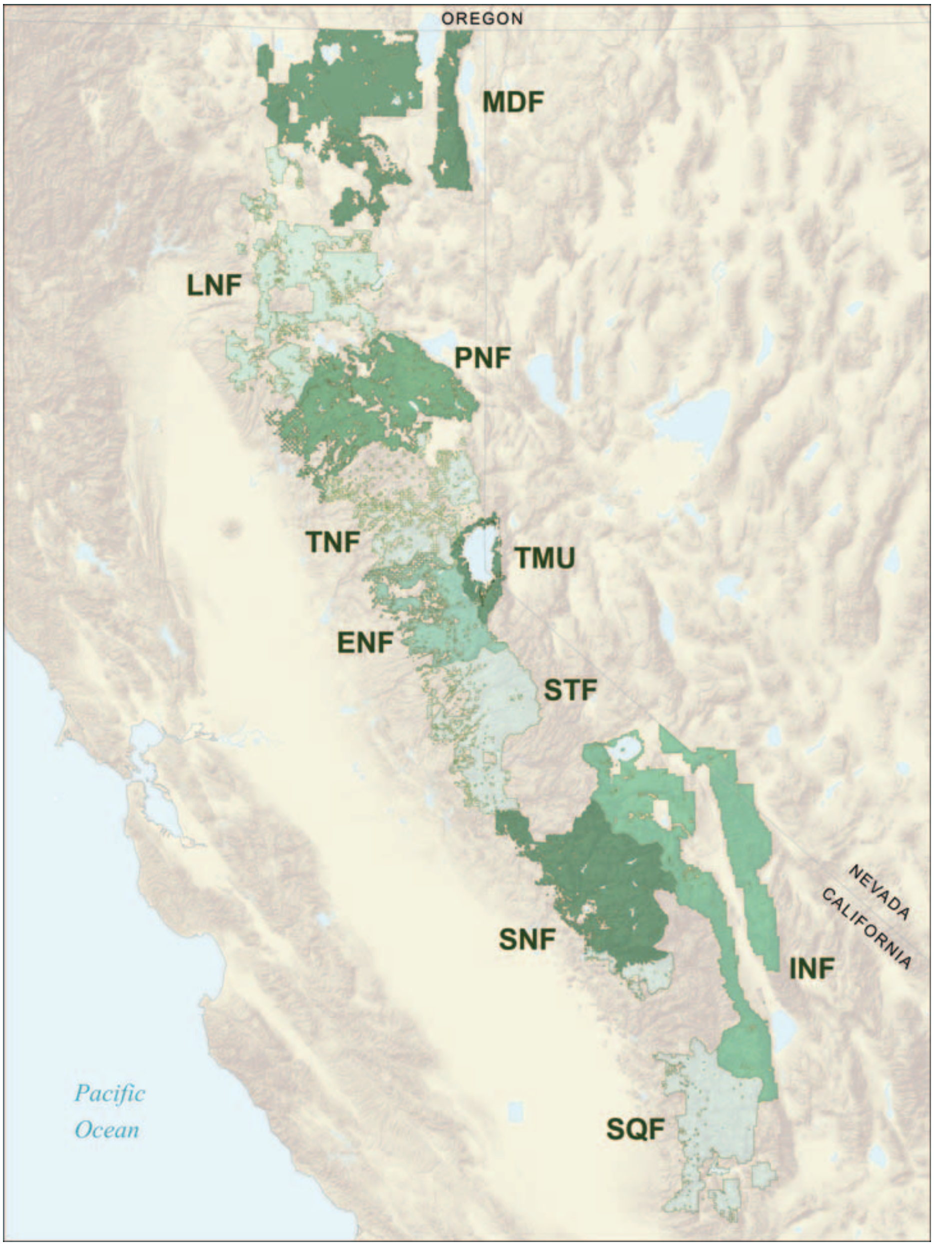

Figure 1. Map of the Sierra Nevada Bioregion used in this analysis. Outlines of the 10 NFs examined are shown and shaded polygons show Forest Service ownership. The NFs are Modoc (MDF), Lassen (LNF), Plumas (PNF), Tahoe (TNF), Eldorado (ENF), Stanislaus (STF), Sierra (SNF), Inyo (INF), and Sequoia (SQF). TMU indicates the Lake Tahoe Basin Management Unit.

quire cable yarding systems, which are not widely used for fuels reduction treatments on Forest Service land in the Sierra Nevada. Distance from existing road impact operations because the Forest Service typically limits construction to temporary roads <1,000 ft long. However, longer access roads may be constructed if there is a resource need and costs can be offset based on timber harvest value. As an indirect measure of economic potential, we used the California Wildlife Habitat Relationship (CWHR) system, a classification widely used by the Forest Service to indicate forest type, average tree size, and canopy cover of different forests (Mayer and Laudenslayer 1988). Forests are classified by a code that indicates the forest type (e.g., SMC for Sierran mixed conifer), size class (1–6, depending on average tree diameter), and canopy cover. We considered forests as having economic potential if they were conifer forest types found in lower to midelevations, with an average tree diameter ≥11 in. and canopy cover ≥40%. In general, forests in the Sierra Nevada that meet these criteria usually have large enough trees to provide merchantable timber, such that fuels reduction treatments could essentially "pay for themselves" (i.e., the value obtained from thinning larger trees could offset the cost of removing smaller, submerchantable trees that often function as ladder fuels). We did not consider small-diameter biomass utilization, as currently there are few facilities to subsidize the costs of removing this material.

Using these factors, we developed four scenarios of operational constraints (A–D). These scenarios capture the range of feasible interpretations of current standards and guides. Scenario A reflects the most strict adherence to current standards and guides where mechanical operations occur on <35% slopes and within 1,000 ft of existing roads (Table 1). Scenario B extends the road building distance to 2,000 ft if more valuable timber is accessed to help defray costs. Scenario C adds working on steeper slopes (35–50%) within 500 ft of existing roads if more valuable timber is accessed. Scenario D accesses all forest (regardless of timber value) on <35% slope within 2,000 ft of existing roads and all forest on 35–50% slope within 1,000 ft of existing roads. Some forests adhere to scenario A constraints particularly if operating in or near riparian areas and sensitive species habitat. Many forests use a combination of scenario B and C, depending on forest and physiographic conditions. Scenario D is rarely used but has been used when there is nontimber, high-resource value to a particular area. As a conservative approach, in some of our analyses we use scenario C to evaluate the effects of less restrictive mechanical constraints on fuels treatment implementation.

Some forestland also limits mechanical treatment through special administrative designation (L3). We included those that are most common in the Sierra Nevada, including riparian zones, California spotted owl (*Strix occidentalis occidentalis*) and northern goshawk (*Accipiter gentilis*) activity centers, and Research Natural Areas (Table 1). Mechanical treatments are not strictly prohibited in these areas, but they are highly restricted and in practice are areas that are often left untreated. For buffer widths on either side of streams we used 100 and 50 ft for perennial and intermittent streams, respectively, following current standards and guidelines (USDA Forest Service 2004). In areas designated as wildland urban interface (Radeloff et al. 2005), restrictions for sensitive species habitat apply to a 500 ft radius around nest or activity center areas. In all other areas, it is 300 and 200 acres for spot-

Table 1. Hierarchy, types, and criteria of mechanical treatment constraints used in our analysis.

Constraint type	Criteria		
L0: Biological			
a. Not timber productive	a. Either nonforest or <10% cover		
b. Water/Barren			
L1: Legal			
a. Wilderness			
b. Recommended wilderness			
c. Inventoried roadless	c. All inventoried roadless except those areas where new road construction is allowed		
L2: Operational	Slope	Road distance	CWHR
A. Existing (most constrained, gentle slope near roads)	<35	<1,000	
B. A plus road distance increase (distance extended for areas with greater economic return)	<35	<1,000	
		<2,000	4, 5 (M and D), 6
C. B plus slope increase (if close to road, slope increased for areas with greater economic return)	<35	<1,000	
		<2,000	4, 5 (M and D), 6
	35–50	<500	4, 5 (M and D), 6
D. C plus all forest types (least constrained by slope, road access and economics)	<35	<2,000	
	35–50	<1,000	
L3: Administrative			
a. Riparian proximity	a. Buffer width: 100 ft perennial; 50 ft intermittent		
b. California spotted owl	b. WUI—500 ft radius; otherwise 300 acres around activity center/nest		
c. Goshawk	c. WUI—500 ft radius; otherwise management identified polygon (mean = 200 acres)		
d. Research natural areas			

The CWHR system is a widely used forest classification with M and D referring to canopy cover of 40–59% and 60–100%, respectively, and 4, 5, and 6 indicating a quadratic mean diameter of 11–24, >24, and >24 in. with a multilayer canopy, respectively. We confined our CWHR forest types to conifers only. WUI, wildland urban interface.

ted owls and goshawks around the nest/activity center, respectively. Although it is an important sensitive species in the Sierra Nevada, we did not include the fisher (*Martes pennanti*) in our analysis because there were no data identifying resting and core activity areas. If their habitat had been included, it would decrease the area available for mechanical treatment, but only on the Sierra and Sequoia NFs where a small (<200 individuals) isolated population of fisher is present (Zielinski et al. 2005).

In an effort to characterize the spatial arrangement of mechanically operable land, we subdivided the SNBR area into discrete geographic units. Earlier analysis of Forest Service managed lands in the SNBR used the concept of "firesheds" to identify meaningful landscape management units. 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 et al. 2007). Although this effort was not completed for the entire region, many of the firesheds that were identified followed subwatershed boundaries. As a unit for our landscape analysis, we used sixth level hydrologic units (HUs) enumerated with 12-digit codes, commonly referred to as "subwatersheds." These units represent an imperfect approximation of potential firesheds. They are generally sized at a scale at which fire containment is initially managed (8,000–40,000 acres), and the ridge tops that separate watersheds commonly provide opportunities for wildfire containment. Omernik (2003) has pointed out that many HUs are smaller than entire watersheds, but for our fire-focused analysis, their topographic delineation may serve as an appropriate initial fireshed classification for forestland in the Sierra Nevada.

We excluded HUs that were not entirely within the SNBR and where Forest Service ownership was <25% of the burnable forest area (excluding bare rock and sparsely vegetated areas). We used this cutoff under the assumption that with <25% ownership, Forest Service treatment alone could not substantially affect wildfire behavior across the subwatershed. For the remaining subwatersheds, we calculated the percentage of the subwatershed's total burnable forest that the Forest Service could mechanically treat. Based on model simulations of how much area generally needs to be treated to influence wildfire behavior, we binned the subwatersheds into three classes of mechanical constraint: high (85–100% [i.e., only 0–15% is available for mechanical treatment]), medium (65–84%), and low (<65%). We chose these levels to identify watersheds where fuels treatment would principally need to rely on fire (those with a high level of mechanical constraint), could use a combination of fire and mechanical thinning (medium), and could effectively influence wildfire behavior with mechanical treatment alone (low). We calculated the percentage of subwatersheds in each of these categories for each NF across the SNBR.

Results

Of the SNBR's 10.7 million acres, 4.5 million acres were nonproductive forestland. The NFs with the largest amount of nonproductive forestland are the Modoc with 63% (mostly sagebrush [*Artemisia* spp.]) and the Inyo with 80% (mostly alpine, rock, and some low-elevation sagebrush) (Figure 2). Focusing on just the productive forestland on each NF (Table 2), legal constraints (wilderness and roadless) reduced mechanically available acreage on average by 22.5% (Table 2). On productive forestlands, legal constraints imposed the largest reduction in mechanically available acreage in the southern (the Stanislaus, Sierra, and Sequoia) and eastern (Inyo) NFs of the bioregion (Table 2).

A comparison of the impact of different operational constraints found a much higher range between scenarios A to D in the northern than the southern parts of the SNBR (Figure 3). In the northern NFs (Modoc, Lassen, Plumas, and Tahoe), there is an average increase in mechanically available acreage of 17% between scenario A (current standard and guides) and D (increasing slope and road access to all productive forest) compared with just a 9.5% increase for the southern and eastern NFs (Stanislaus, Sierra, Sequoia, and Inyo) (Figure 3). Changing operational constraints from scenario A to B (greater access distance from existing roads for large trees) increased mechanical acreage on average about 2–3% in the southern part of the range but up to about 6–7% in the northern NFs (Figure 3). The greater increase in northern NFs results because the increased operational "reach" from existing roads tends not to overlap as much with legal constraints such as wilderness and roadless areas, which limit the effect of easing the operational constraints in the southern NFs. There was little increase in available acreage between operational constraint scenarios B and C (adding steeper slopes close to roads for large trees), regardless of NF. The relatively greater increase between scenarios C and D (increased access to *all* productive forests) reflects the limited amount of large-tree forests, particularly in the northern extent of the SNBR. Focusing on scenario C, operational constraints reduced productive forestland available for mechanical treatment on average by 25.6% (Table 2).

The percent reduction of mechanically available acreage with administrative constraints (riparian zones, sensitive species habitat, and Research Natural Areas) varied widely between different NFs. Whereas the overall reduction averaged 8.1% (Table 2), NFs generally fell into two equal-sized classes with either a modest reduction of 1.9–6.3% (Inyo, Modoc, Sequoia, Lassen, and Lake Tahoe Basin Management Unit [TMU]) or a higher reduction of 9.2–13.2% (Sierra, Tahoe, Eldorado, Plumas, and Stanislaus). What drove this difference was the distribution of sensitive species habitat, particularly that of spotted owls, because Research Natural Areas are small and riparian constraints were fairly similar between NFs.

We identified 710 subwatersheds across the SNBR for further analysis using our rule of Forest Service managed area being >25% of the total burnable area. On average, 46, 34, and 20% of the subwatersheds were highly, moderately, and lightly mechanically constrained, respectively (Table 3). The constrained area was determined using L0–L3, scenario C (Table 1). Half of SNBR's NFs (Stanislaus, Modoc, Sierra, Sequoia, and Inyo) have ≥50% of their subwatersheds highly constrained in which mechanical treatment alone is too limited to affect wildfire behavior or containment. Only the Lassen, Plumas, and Tahoe NFs have >25% of their subwatersheds lightly mechanically constrained (Table 3). A range-wide map of subwatersheds shaded by constraint level (Figure 4) indicates mechanically constrained areas tend to be clustered. The Modoc NF and the forests in the southern and eastern Sierra Nevada have large contiguous areas in which mechanical treatments make up a small percentage of each subwatershed's burnable acres.

A closer examination of the subwatersheds on a portion of the Sierra NF demonstrates the wide array of patterns in mechanical operability, ranging from large clusters to highly dispersed numerous small fragments (Figure 5). In highly constrained subwatersheds, mechanical treatment alone probably will have a limited and localized effect on reducing potential fire intensity and size (e.g., subwatersheds in the lower left and lower right of Figure 5 with 13 and 10% mechanically available). In subwatersheds with moderate constraint levels, mechanical treatment alone can affect wildfire for some or most of the subwatershed's area depending on configuration (e.g., upper middle and lower middle subwatersheds with 23 and 20% in Figure 5). Mechanically treatable areas in subwatersheds with only a light constraint level are often large and numerous enough that they can achieve most of the subwatershed's desired fuels reduction with mechanical treatment alone (e.g., center and upper middle subwatersheds with 36 and 57% in Figure 5).

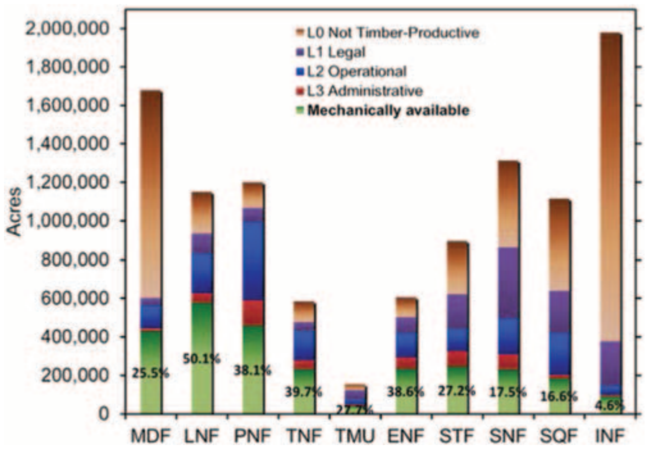

Figure 2. Histogram of how constraints reduce *total* acreage available to mechanical treatment in Sierra Nevada NFs. The height of the bar indicates each NF's total acres, with each constraint designated by a different color. The acreage available for mechanical treatment is what remains in the green portion of each bar and is indicated by the percentage values. Forests are arranged from northern most to southern along the western slope and the Inyo on the eastern slope. The L2 constraint uses scenario C (see Table 1).

Table 2. Productive forest acreage (L0) of each NF and the percent reduction of different types of constraints on mechanical treatment.

NF	L0: Productive forest (acres)	L1: Legal	L2: Operational	L3: Administration	Total remaining (acres)	% of productive forest
		. . . .	. . (%) . .	. . . .		
Modoc	602,209	−7.1	−18.9	−2.9	428,223	71.1
Lassen	935,571	−11.0	−21.9	−5.5	575,845	61.6
Plumas	1,065,594	−7.0	−37.6	−12.6	456,714	42.9
Tahoe	474,902	−8.9	−32.6	−9.8	231,276	48.7
TMU	121,434	−37.8	−21.5	−6.3	41,882	34.5
Eldorado	499,798	−16.3	−25.2	−11.8	233,448	46.7
Stanislaus	621,032	−28.9	−18.7	−13.2	243,774	39.3
Sierra	864,993	−42.8	−21.4	−9.2	229,502	26.5
Sequoia	639,808	−34.9	−33.2	−3.0	185,156	28.9
Inyo	376,325	−61.6	−12.3	−1.9	91,280	24.3
Total	6,201,666	−22.5	−25.6	−8.1	2,717,100	43.8

Constraints L1–L3 are the percentages of reduction in productive (in contrast to total forest acreage in Figure 2) forest. L2 reduction uses scenario C (see Table 1). Total remaining is the number of productive forest acres that are available for mechanical treatment after all constraints are applied.

Discussion

In California's Sierra Nevada forests, mechanical treatment is often considered the only practical large-scale fuels reduction strategy because there are many limitations on using fire (Williamson 2008, Quinn-Davidson and Varner 2012). Our analysis,

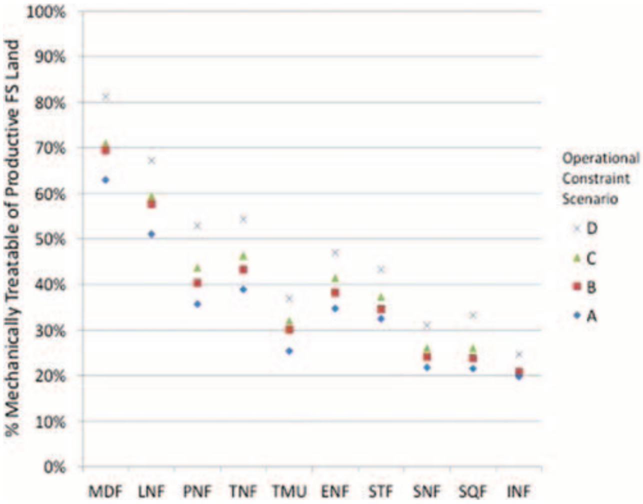

Figure 3. Symbols show the percentages of mechanically available productive forestland left on each NF under four different operational constraint scenarios (i.e., scenarios A–D [see L2 criteria in Table 1]) after all four constraint levels, L0–L3, are applied. The difference between the four scenarios (A is the most restrictive and D is the least constrained) indicates how sensitive the amount of mechanically available acreage is to different road distance, slope, and economic variables.

Table 3. Number of subwatersheds on each NF with ≥25% USDA Forest Service ownership of all burnable acres.

	HUs		Level of constraint		
NF	Total	>25% USDA FS	High (85–100%)	Moderate (65–84%)	Light (<65%)
			. . . .	.(%).	
Modoc	144	96	51.0	32.3	16.7
Lassen	150	98	22.4	39.8	37.8
Plumas	111	87	20.7	44.8	34.5
Tahoe	90	54	24.1	48.1	27.8
TMU	27	16	37.5	50.0	12.5
Eldorado	65	50	26.0	50.0	24.0
Stanislaus	80	53	49.7	30.2	20.1
Sierra	92	77	66.2	15.6	18.2
Sequoia	103	70	72.9	22.8	4.3
Inyo	167	109	91.7	3.7	4.6
Total	1,029	710			
Average			46.2	33.7	20.1

The level of constraint values are the percentages of each NF subwatershed in which mechanical treatment is highly (85–100%), moderately (65–84%), and lightly (<65%) constrained using operational scenario C. The three categories are calculated based on the number of Forest Service acres available to mechanical treatment divided by the total burnable acres (across all ownerships) within the HU.

however, found that in many Forest Service managed areas, there are considerable areal constraints on mechanical treatment, suggesting that mechanical treatment alone may not be able to effectively increase the pace and scale of fuels reduction and forest restoration in much of the Sierra Nevada. The small amount of mechanically treatable acreage in 46% of subwatersheds and the often suboptimal distribution in another 34% of subwatersheds (Table 3), suggests that there is a limited ability to create effective extensive fuels treatments by mechanical methods alone. If mechanically available areas, however, are used as anchors from which to expand fire-based fuels reduction, the pace and scale of fuels treatment and forest restoration might be accelerated in many subwatersheds across the Sierra Nevada. Although our analysis focuses on the Sierra Nevada, other mountainous western US areas with productive forests may have similarly high levels of mechanical constraint due to extensive wilderness and roadless areas and steep terrain limiting access.

Our analysis has several limitations. One clear weakness is that we cannot capture what management may occur on private lands that may or may not complement Forest Service fuels reduction objectives. These activities may significantly affect the impact of Forest Service mechanical fuels reduction particularly in moderate constraint level subwatersheds (e.g., in Figure 5 the upper left subwatershed with 20%, where much of the private ownership around Shaver Lake has had treatments by a private owner, Southern California Edison). The data sets used in this analysis may also fail to recognize numerous more localized operational constraints based on topography, additional protections (e.g., archeological and cultural sites), and treatment histories. Project plans may justify treatments in areas that are typically constrained (e.g., owl core areas) or have special practices in riparian buffers. Our analysis is intended to operate at a broad scale for planning, not a project-specific one. In general, the three constraint levels provide broad qualitative categories for subwatersheds where mechanical fuels reduction may have limited impact, will need to be strategically examined (considering configuration and other ownership management practices), or can be highly effective.

To check our analysis, we did compare our results with actual treatment plans on several NFs and found that there was a high level of consistency between areas that were not treated and areas that we identified as constrained. Our geographic information system (GIS) analysis may help inform forest planning efforts and serves as a useful communication tool for describing the feasibility of various treatment scenarios to public stakeholders.

Our analysis yielded strikingly different results from a similar analysis undertaken in the ponderosa pine (*Pinus ponderosa*) belt of Central Arizona (Hampton et al. 2011), which found that 78% of that landscape was potentially available to mechanical restoration thinning treatments. Key differences between the two regions include a much higher percentage of wilderness and roadless areas and greater constraints due to steep slopes in the Sierra Nevada. Areas with conditions analogous to the Sierra Nevada, however, are widespread in much of the western United States, particularly in more mountainous areas with productive forests, such as most of the Rocky Mountain lower and midelevation forests.

Economics constrains mechanical operability in the Sierra Nevada more than road building and steep slope limitations (Figure

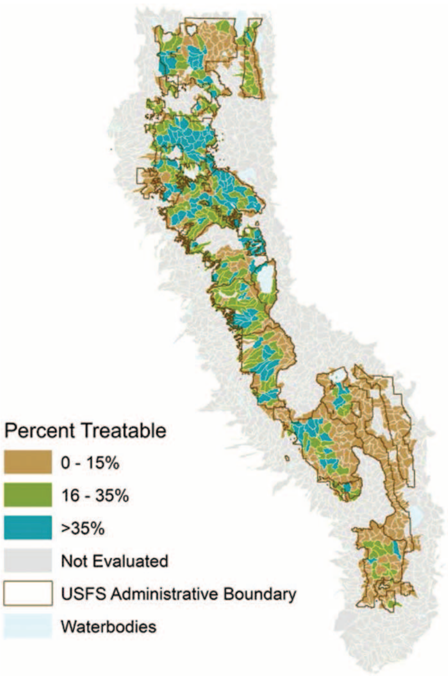

Figure 4. Sierra Nevada Bioregion divided into subwatersheds (HU12). Shadings indicate percentages of the total burnable acres that are available for the Forest Service to mechanically treat: gray, FS ownership <25%; brown, 0–15%; green, 16–35%; and blue, >35%.

3). Relaxing the allowable length of newly constructed road to access merchantable trees improved access more in the northern than in the southern NFs (scenario B). Operating on steeper slopes with large trees (scenario C) only slightly increased access regardless of location (scenarios A and B). This suggests that increasing use of temporary roads or alternative harvesting strategies (i.e., cable yarding) may not substantially ease constraints on mechanical operability. There is a larger increase in accessible acres when longer access roads are built and steeper slopes are treated without considering the need to offset these increased costs with timber revenues (Figure 3, scenario D). Given the current limited budgets for fuels treatment, this scenario is unlikely to be widely used. Over the next few decades, operational constraints may not change much until trees become large enough in less accessible areas to support higher costs of harvest.

Restrictions around sensitive species habitat are often considered a significant constraint on widespread fuels treatments (Keele et al. 2006). However, we found that on only 3 of the 10 NFs did these constraints reduce acreage by >10% (Table 2), after accounting for legal (wilderness and roadless designation) and operational (remote and steep slopes) constraints. In our analysis, the percent area removed (Table 2) was hierarchical from L0 to L3, meaning that for each successive level, we only report the additional area removed. This partially explains the relatively low percentages associated with the administrative constraints (L3, Table 2). Administrative constraints have the largest impact when operational constraints are relaxed to access merchantable trees. Larger trees (i.e., 20–29 in. dbh) are common in the preferred habitat for sensitive species (Berigan et al. 2012, Zielinski et al. 2013). These areas also have some of the highest fuel loads of SNBR forests (Spies et al. 2006), yet are generally left untreated due to concerns over potential resource damage and litigation.

Refinements in fire modeling have improved our understanding of optimal treatment size and location (Finney 2007, Ager et al. 2010, 2013), but extensive fuels treatment effectiveness can be limited when management is focused primarily on mechanical methods. Although the initial models suggested that a herringbone pattern of fuels treated areas is most effective in an idealized landscape (Finney 2001), multiple case studies (Collins et al. 2011, 2013) demonstrate that treating what is available can still be highly effective if the treated area is ≥20% of the landscape and generally perpendicular to prevailing wind and likely fire movement direction. For many SNBR subwatersheds, however, we found that mechanically available acreage may not be strategically oriented (relative to the dominant wind pattern) or arranged (too skewed or clumped) to effectively disrupt landscape-level fire spread and effects (Finney 2001). Furthermore, some areas would remain susceptible to wildfire spread due to untreated "stringers" (Figure 5). Some of these long linear mechanical exclusion zones are remote or steeply sloped areas, but many are riparian areas. Riparian zones often perforate mechanically treatable areas, yet leaving these areas untreated can significantly compromise fuels treatment effectiveness. Many riparian areas in the Sierra Nevada burned as frequently as adjacent upland forests, but given their higher productivity, often now have some of the highest fuels in the Sierra Nevada (Van de Water and North 2010, 2011). For riparian areas, designing treatments to specific characteristics of streams within a landscape may afford protections while reducing the fragmentation associated with standardized buffers (Hunsaker and Long 2014). Current policies appear to provide managers with some flexibility as long as they provide justification for riparian area treatment. If riparian buffers were treated with either thinning and/or fire, their wildfire wicking potential might be significantly reduced, increasing mechanical treatment effectiveness.

The subwatershed maps generated by this analysis indicate that the collective constraints on mechanical treatment may limit opportunities for effective extensive fuel reduction. Although it is possible that hand thinning could be substantially expanded, this is unlikely given the high cost per unit area and overall lack of funding. Recent noncommercial projects in the SNBR area demonstrate the economic limitations associated with removing only nonmerchantable trees (i.e., Cedar Valley and Sugar Pine Projects, Sierra NF). In an analysis conducted in the Stanislaus NF, Finney et al. (2007) noted that once constraints reserved 45% of the area from treatment, strategically placed fuels treatments performed no better than random placement. In our analysis, 8 of the 10 NFs in the SBNA had mechanical constraints on >45% of their productive forestland (Table 2). Some of these constraints are relatively fixed by policy or by nature, but others have been designed as temporary safeguards to minimize impacts to sensitive species and areas through administrative rules. To facilitate landscape-scale restoration, it may be important to relax these constraints in an adaptive management approach, such as within landscape demonstration areas (North et al. 2014). Another alternative is to apply threshold values for disturbance over time (Zielinski et al. 2013) at larger scales to mitigate impacts to sensitive wildlife species.

Our analysis suggests that in many areas a wildfire policy focused on containment and suppression is unlikely to be effective if it relies primarily on mechanical fuels reduction methods. Although fire models can help identify areas with higher burn probabilities (Ager et al. 2010, 2013), effective containment and suppression hinges on treatment placement (Syphard et al. 2011). In many SNBR subwatersheds current constraints rarely optimize mechanical treatment locations. Furthermore, mechanically maintaining reduced fuel loads in treated areas eventually consumes all of the fuels treatment effort, leading to a backlog of forest that never gets treated. By one estimate, >60% of productive forests in the Sierra Nevada will remain in the

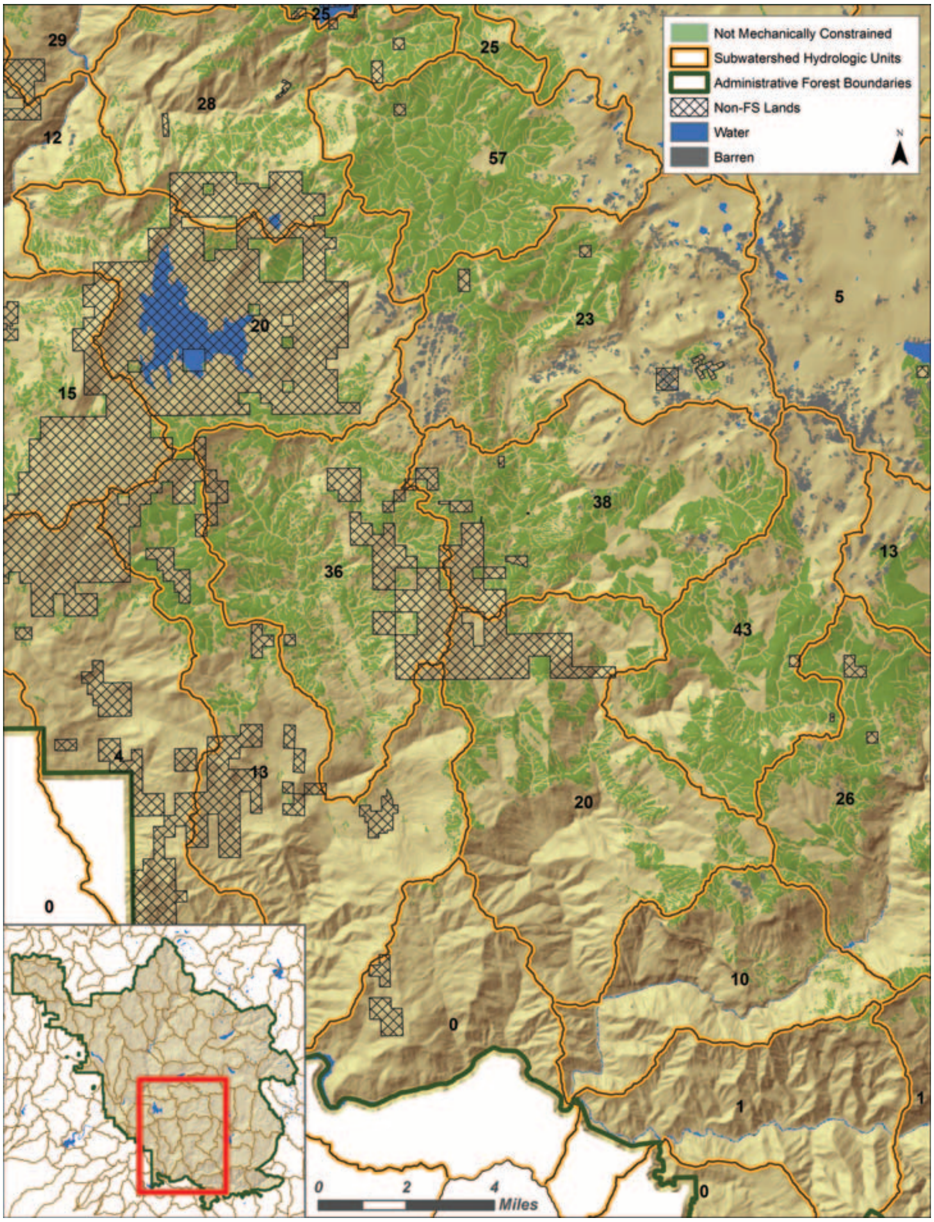

Figure 5. Adjacent subwatersheds (orange outlines) in the Dinkey Creek (middle) and Shaver Lake (upper left) area of the Sierra NF. Green shading indicates areas that can be mechanically treated, and the bold values indicate the percentages of total burnable forest within the subwatershed that can be mechanically treated by the Forest Service under operational constraint scenario C.

backlog of fuel-loaded forests at current treatment rates (North et al. 2012).

In most subwatersheds, the most effective use of mechanically treatable areas may be as "safe zone" anchors for wider reintroduction of fire. For example, the 10% subwatershed in Figure 5 has a few lower slope mechanically treatable areas (near the river), but fire-based fuels reduction is needed to effectively connect these areas to upper slope/ridgetop mechanically unconstrained areas. Large prescribed burns commonly used in western Australia are possible because a network of low-fuel "anchors" (previous burns, rocky areas, and low-fuel forests) allow 6–8% of the forest to be burned annually (Sneeuwjagt et al. 2013). Although the outcomes of fuels reduction by prescribed burn and managed wildfire are less precise or "surgical" at the stand level, across a landscape it can be much more effective than relying on constrained mechanical treatments. Mechanical treatment still is probably the most practical fuels treatment in the wildland urban interface, and opportunities for extensive use of managed fire may be further reduced during extended droughts. However, under moderate weather conditions and in remote locations, prescribed burning may be more efficient, cost-effective, and ecologically beneficial (North et al. 2012) than extensive mechanical treatments. Using machine harvest to establish more anchors for fire reintroduction would also generate forest products that provide economic opportunities for rural communities with processing infrastructure.

Our analysis suggests that the current heavy reliance on mechanical fuels reduction is unlikely to effectively contain or suppress wildfire in many areas of the Sierra Nevada. Too much NF area is unavailable for mechanical treatment and what is available is often too small and scattered to effectively alter landscape-level fire spread and intensity. However, significant increases in treatment pace and scale are possible if mechanical thinning is used to facilitate larger prescribed burns and enable managed wildfire. Wildfire size and intensity are predicted to increase under future projected climate scenarios (Lenihan et al. 2003, Lenihan et al. 2008), suggesting that fire policy and forest restoration might benefit if mechanical thinning is more widely used to leverage and complement managed fire.

Endnotes

1. In this article, we use the term mechanical treatment to refer to machine-based fuels reduction and tree harvest (i.e., use of ground-based heavy equipment such as feller-bunchers and skidders). We did not include hand thinning with chainsaws within our scope of mechanical treatments because high costs and slow pace constrain its effectiveness for reducing fuels in the Sierra Nevada.
2. The GIS analysis, data layers, and more detailed methods are available at https://fs.usda.gov/wps/PA_WIDContribution/widct/previewhtml.jsp?param1=STELPRDB5327833&param2=text/html&param3=1646948.

Literature Cited

Agee, J.K., and C.N. Skinner. 2005. Basic principles of forest fuel reduction treatments. *For. Ecol. Manage.* 211:83–96.

Ager, A., B. Bahro, and K. Barber. 2006. Automating the fireshed assessment process with ArcGIS. P. 28–30 in *Fuels management—How to measure success: Conference proceedings*, Andrews, P.L., and B.W. Butler (eds.). USDA For. Serv., Proc. RMRS-P-41, Rocky Mountain Research Station, Fort Collins, CO.

Ager, A.A., N.M. Vaillant, and M.A. Finney. 2010. A comparison of landscape fuel treatment strategies to mitigate wildland fire risk in the urban interface and preserve old forest structure. *For. Ecol. Manage.* 259:1556–1570.

Ager, A.A., N.M. Vaillant, and A. McMahan. 2013. Restoration of fire in managed forests: A model to prioritize landscapes and analyze tradeoffs. *Ecosphere* 4:art29.

Bahro, B., K.H. Barber, J.W. Sherlock, and D.A. Yasuda. 2007. Stewardship and fireshed assessment: A process for designing a landscape fuel treatment strategy. P. 41–54 in *Restoring fire-adapted ecosystems: 2005 national silviculture workshop*, Powers, R.F. (ed.). USDA For. Serv., Gen. Tech. Rep. PSW-GTR-203, Pacific Southwest Research Station, Albany, CA.

Berigan, W.J., R.J. Gutierrez, and D.J. Tempel. 2012. Evaluating the efficacy of protected habitat areas for the California spotted owl using long-term monitoring data. *J. For.* 110: 299–303.

Collins, B.M., H.A. Kramer, K.M. Menning, C. Dillingham, D. Saah, P.A. Stine, and S.L. Stephens. 2013. Modeling hazardous fire potential within a completed fuel treatment network in the northern Sierra Nevada. *For. Ecol. Manage.* 310:156–166.

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., S.L. Stephens, G.B. Roller, and J.J. Battles. 2011. Simulating fire and forest dynamics for a landscape fuel treatment project in the Sierra Nevada. *For. Sci.* 57:77–88.

Donovan, G.H., and T.C. Brown. 2005. An alternative incentive structure for wildfire management on national forest land. *For. Sci.* 51:387–395.

Finney, M.A. 2001. Design of regular landscape fuel treatment patterns for modifying fire growth and behavior. *For. Sci.* 47:219–228.

Finney, M.A. 2007. A computational method for optimising fuel treatment locations. *Int. J. Wildl. Fire* 16:702–711.

Finney, M.A., R.C. Seli, 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. Wildl. Fire* 16:712–727.

Fule, P.Z., J.E. Crouse, J.P. Roccaforte, and E.L. Kalies. 2012. Do thinning and/or burning treatments in western USA ponderosa or Jeffrey pine-dominated forests help restore natural fire behavior? *For. Ecol. Manage.* 269: 68–81.

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.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. Policy Econ.* 10:344–354.

Hunsaker, C., and J. Long. 2014. Forested riparian areas. P. 323–340 in *Science synthesis to support socioecological resilience in the Sierra Nevada and southern Cascade Range,* Long, J., L. Quinn-Davidson, and C. Skinner (eds.). USDA For. Serv., Gen Tech. Rep. PSW-GTR-247, Pacific Southwest Research Station, Albany, CA.

Keele, D.M., R.W. Malmsheimer, D.W. Floyd, and J.E. Perez. 2006. Forest Service land management litigation 1989–2002. *J. For.* 104:196–202.

Lee, D.C., and L.L. Irwin. 2005. Assessing risks to spotted owls from forest thinning in fire-adapted forests of the western United States. *For. Ecol. Manage.* 211:191–209.

Lenihan, J.M., D. Bachelet, R.P. Neilson, and R. Drapek. 2008. Response of vegetation distribution, ecosystem productivity, and fire to climate change scenarios for California. *Climatic Change* 87(Suppl. 1):S215–S230.

Lenihan, J.M., R. Drapek, D. Bachelet, and R.P. Neilson. 2003. Climate change effects on vegetation distribution, carbon, and fire in California. *Ecol. Appl.* 13:1667–1681.

Mayer, K.E., and W.F. Laudenslayer. 1988. *A guide to wildlife habitats of California*. California Department of Fish and Wildlife, Sacramento, CA. 166 p.

North, M., B. Collins, J. Keane, J. Long, C. Skinner, and W. Zielinski. 2014. Synopsis of emergent approaches. P. 55–70 in *Science synthesis to support socioecological resilience in the Sierra Nevada and southern Cascade Range,* Long, J., L. Quinn-Davidson, and C. Skinner (eds.) USDA For. Serv., Gen. Tech. Rep. PSW-GTR-247, Pacific Southwest Research Station, Albany, CA.

North, M., B.M. Collins, and S. Stephens. 2012. Using fire to increase the scale, benefits, and future maintenance of fuels treatments. *J. For.* 110:392–401.

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., Gen Tech. Rep. PSW-GTR-220, Pacific Southwest Research Station, Albany, CA. 49 p.

Omernik, J.M. 2003. The misuse of hydrologic unit maps for extrapolation, reporting and ecosystem management. *J. Am. Water Resour. Assoc.* 39:563–573.

Quinn-Davidson, L.N., and J.M. Varner. 2012. Impediments to prescribed fire across agency, landscape and manager: An example from northern California. *Int. J. Wildl. Fire* 21:210–218.

Radeloff, V.C., R.B. Hammer, S.I. Stewart, J.S. Fried, S.S. Holcomb, and J.F. McKeefry. 2005. The wildland-urban interface in the United States. *Ecol. Appl.* 15:799–805.

Reinhardt, E.D., R.E. Keane, D.E. Calkin, and J.D. Cohen. 2008. Objectives and considerations for wildland fuel treatment in forested ecosystems of the interior western United States. *For. Ecol. Manage.* 256:1997–2006.

Sneeuwjagt, R.J., T.S. Kline, and S.L. Stephens. 2013. Opportunities for improved fire use and management in California: Lessons from western Australia. *Fire Ecol.* 9(2):14–25.

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., J.D. McIver, R.E. Boerner, C.J. Fettig, J.B. Fontaine, B.R. Hartsough, P.L. Kennedy, and D.W. Schwilk. 2012. The effects of forest fuel-reduction treatments in the United States. *Bioscience* 62:549–560.

Stephens, S.L., and L.W. Ruth. 2005. Federal forest-fire policy in the United States. *Ecol. Appl.* 15:532–542.

Syphard, A.D., R.M. Scheller, B.C. Ward, W.D. Spencer, and J.R. Strittholt. 2011. Simulating landscape-scale effects of fuels treatments in the Sierra Nevada, California, USA. *Int. J. Wildl. Fire* 20:364–383.

Theobald, D.M. 2005. Landscape patterns of exurban growth in the USA from 1980 to 2000. *Ecol. Soc.* 10:32.

Theobald, D.M., and W.H. Romme. 2007. Expansion of the US wildland—Urban interface. *Landsc. Urban Plan.* 83:340–354.

USDA Forest Service. 2004. *Sierra Nevada forest plan amendment*. USDA For. Serv., Final Suppl. Environ. Impact Statement R5-MB-046, Pacific Southwest Region, Albany, CA.

USDA Forest Service. 2012. *Final programmatic environmental impact statement: National Forest System land management planning*. USDA For. Serv., Washington, DC. 333 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.

Williamson, M.A. 2008. Factors in United States Forest Service district rangers' decision to manage a fire for resource benefit. *Int. J. Wildl. Fire* 16:755–762.

Zielinski, W.J., J.A. Baldwin, R.L. Truex, J.M. Tucker, and P.A. Flebbe. 2013. Estimating trend in occupancy for the southern Sierra fisher *Martes pennanti* population. *J. Fish Wildl. Manage.* 4:3–19.

Zielinski, W.J., R.L. Truex, F.V. Schlexer, L.A. Campbell, and C. Carroll. 2005. Historical and contemporary distributions of carnivores in forests of the Sierra Nevada, California, USA. *J. Biogeogr.* 32:1385–1407.