Fuel treatment effects on modeled landscape-level fire behavior in the northern Sierra Nevada

Jason J. Moghaddas, Brandon M. Collins, Kurt Menning, Emily E.Y. Moghaddas, and Scott L. Stephens

Abstract: Across the western United States, decades of fire exclusion combined with past management history have contributed to the current condition of extensive areas of high-density, shade-tolerant coniferous stands that are increasingly prone to high-severity fires. Here, we report the modeled effects of constructed defensible fuel profile zones and group selection treatments on crown fire potential, flame length, and conditional burn probabilities across 11 land allocation types for an 18 600 ha study area within the northern Sierra Nevada, California. Fire modeling was completed using FlamMap and FARSITE based on landscape files developed with high-resolution aerial (IKONOS) imagery, ground-based plot data, and integrated data from ARCFUELS and the Forest Vegetation Simulator. Under modeled 97th percentile weather conditions, average conditional burn probability was reduced between pre- and post-treatment landscapes. A more detailed simulation of a hypothetical fire burning under fairly severe fire weather, or "problem fire", revealed a 39% reduction in final fire size for the treated landscape relative to the pre-treatment condition. To modify fire behavior at a landscape level, a combination of fuel treatment strategies that address topographic location, land use allocations, vegetation types, and fire regimes is needed.

Résumé : Partout dans l'ouest des États-Unis, des décennies d'exclusion du feu combinée aux pratiques d'aménagement passées ont contribué à la situation actuelle caractérisée par de vastes superficies de peuplements de conifères tolérants à l'ombre qui sont de plus en plus sujets à des feux de sévérité élevée. Ici, nous rapportons les effets de la construction de coupe-feu ombragés et de traitements de jardinage par groupe sur le potentiel de feu de cime, la longueur de flamme et les probabilités de brûlage conditionnel parmi 11 types d'affectation des terres dans une aire d'étude de 18 600 ha située dans la partie septentrionale de la Sierra Nevada, en Californie. La modélisation du feu a été réalisée à l'aide de FlamMap et de FARSITE sur la base de fichiers de paysage élaborés à partir de l'imagerie aérienne (IKONOS) à haute résolution, de données terrain provenant de placettes échantillons et de données intégrées provenant de ARCFUELS et du Simulateur de végétation forestière. Sur la base de conditions météorologiques modélisées au 97^{e} percentile, la probabilité moyenne de brûlage conditionnel était réduite en comparant les paysages pré- et post-traitement. Une simulation plus détaillée d'un feu hypothétique brûlant dans des conditions météorologiques assez sévères, ou un feu problématique, a révélé que la dimension finale du feu était réduite de 39 % dans le cas du paysage traité relativement à la situation antérieure au traitement. Pour modifier le comportement du feu à l'échelle du paysage, il faut avoir recours à une combinaison de stratégies de traitement des combustibles qui tiennent compte de la situation topographique, de l'affectation des terres, du type de végétation et du régime des feux.

[Traduit par la Rédaction]

Introduction

Like other forested regions of the western United States, the mid-elevation band within the Sierra Nevada, California, contains vast areas of high-density coniferous forests that are increasingly prone to high-severity fires (Miller et al. 2009). Historic factors contributing to these conditions include a reduction of anthropogenic burning by Native Americans during the mid- to late 19th century (Anderson 2005), removal of large trees through the early 20th century via railroad logging (Stephens 2000), a nearly 100 year policy of fire exclusion (Stephens and Ruth 2005), and extensive use of even-aged management and overstory removals on public lands through the 1980s (Hirt 1996). Trends of both increased fire sizes and uncharacteristically severe burning have been demonstrated throughout the region (Miller et al. 2009) and increasing fire sizes are expected to continue under changing climates (Westerling et al. 2006). For decades, scientists and managers have understood the threat fire would pose to forests in this condition (Biswell 1989). In the

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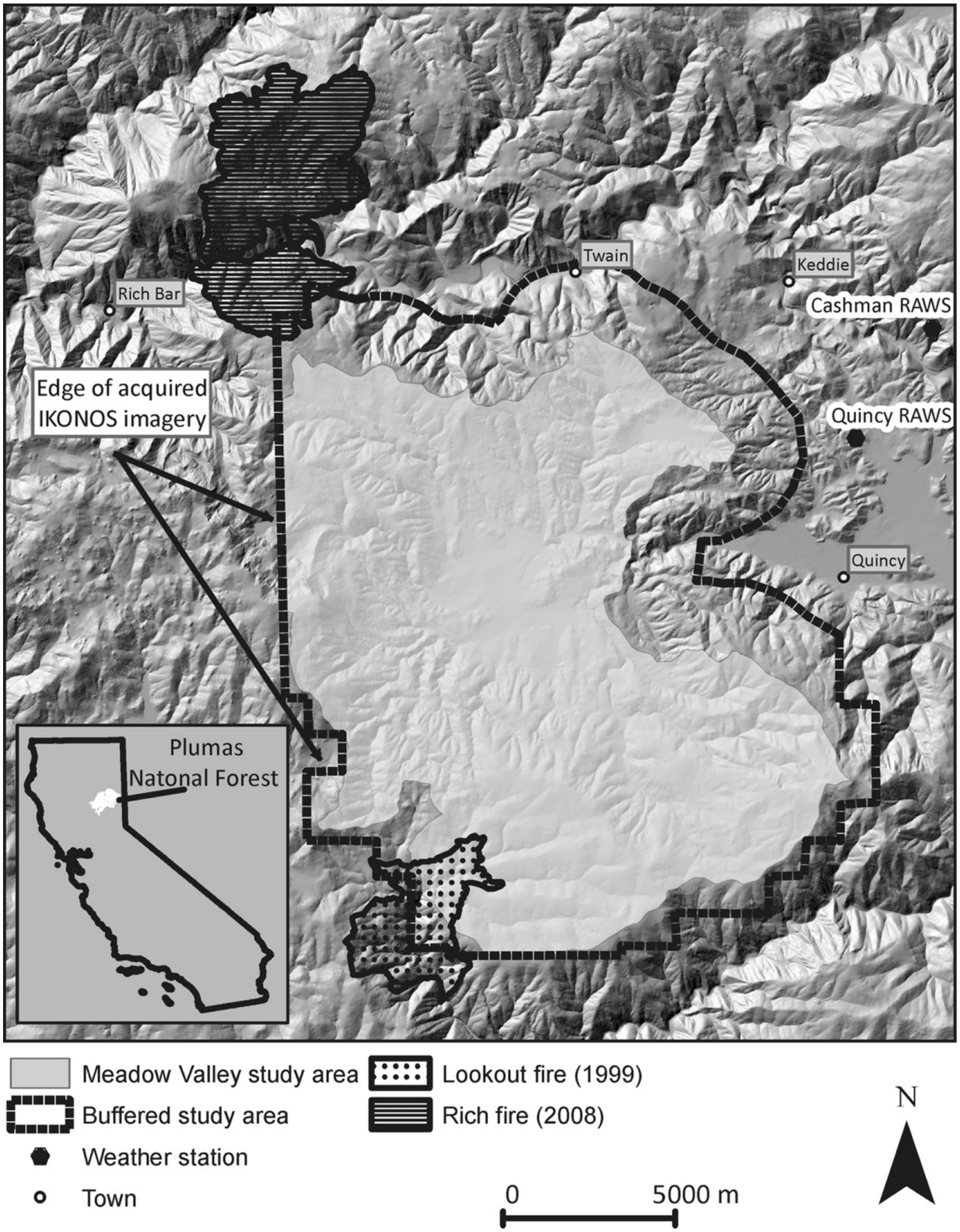
J.J. Moghaddas[1] and S.L. Stephens. Division of Ecosystem Science, Department of Environmental Science, Policy, and Management, University of California, 137 Mulford Hall, Berkeley, CA 94720-3114, USA.
B.M. Collins. USDA Forest Service, Pacific Southwest Research Station, 1731 Research Park Drive, Davis, CA 95618, USA.
K. Menning. Geography and Human Environmental Studies, San Francisco State University, 1600 Holloway Avenue, HSS Room 279, San Francisco, CA 94132, USA.
E.E.Y. Moghaddas. USDA Forest Service, Pacific Southwest Research Station, P.O. Box 15, Taylorsville, CA 95983, USA.

[1]Corresponding author (e-mail: jmoghad@gmail.com).

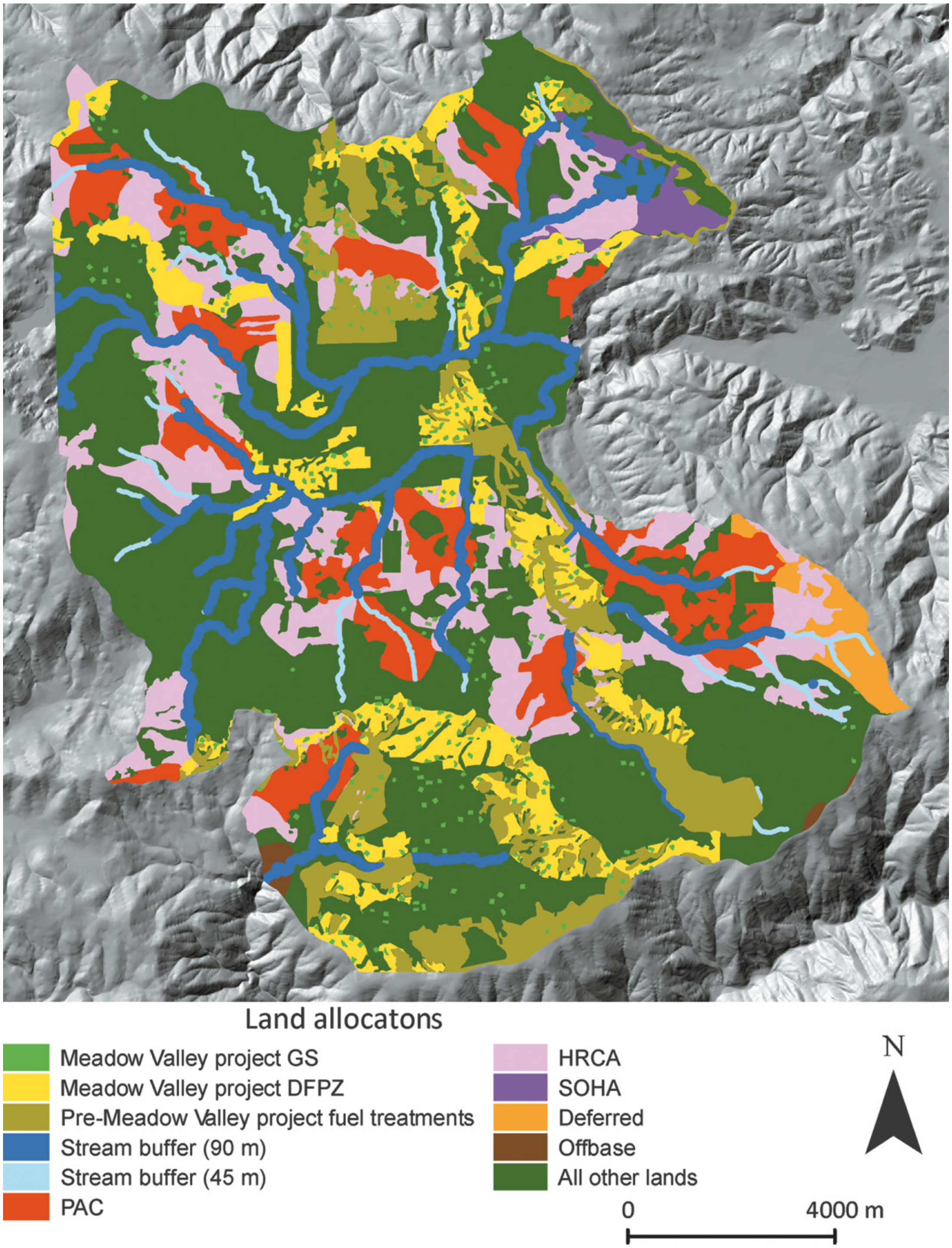
Fig. 1. Meadow Valley study area within the Plumas National Forest. The edge of acquired IKONOS imagery is identified to point out where the study area could not be buffered. We used weather data from both the Quincy and Cashman remote automated weather stations (RAWS). The towns are displayed for reference and to show proximity of the study area to communities.



western United States, it was not until the early 1990s that federal land management agencies were given direction to manipulate stands, using a combination of silvicultural prescriptions, with the specific objective of modifying landscape-level fire behavior.

Many stand-scale studies have demonstrated the effectiveness of various fuel treatment alternatives at changing the behavior and reducing the impacts of both computer-modeled fires (Stephens and Moghaddas 2005; Stephens et al. 2009) and actual wildland fires (Ritchie et al. 2007; Safford et al. 2009). These studies document treatment effects on fire behavior across several treatment types and provide guidance on designing prescriptions for forest stands. However, the extensive tracts of relatively homogenous, fire-excluded forests throughout the western United States and the large wildfires that can occur in these forests demonstrate the pressing need to “scale up” insights gained at the stand level to larger landscapes. However, implementing fuel

Fig. 2. Land allocation and designation for the Meadow Valley study area. DFPZ, defensible fuel profile zone; GS, group selection; PAC, protected activity center; HRCA, home range core area; SOHA, spotted owl habitat area. There was overlap in some allocations and designations; see the Methods section for an explanation.



treatments across an entire landscape over a short period of time is difficult — there is simply too much forest needing immediate treatment (Collins et al. 2010). In addition, both public and private forestlands are often constrained by administrative or regulatory rules that limit silvicultural treatment options within a landscape. Certain designations, or land allocations, limit the range of fuel treatment options or restrict such activities all together. Examples of such land allocations include habitat for sensitive wildlife species and watercourse buffer zones. These land allocations potentially constrain the three important components of any fuel treatment project: location of treatments, treatment type, and size of individual treatment units (Collins et al. 2010). The impacts that these types of constraining land allocations have on fuel treatment implementation and overall effectiveness at reducing adverse fire effects have not been well studied.

Table 1. Vegetation and canopy structure characteristics for each fuel model class based on IKONOS imagery derived layers used in spatial fire modeling.

Scott and Burgan (2005) surface fuel model	Description of fuel class and its occurrence throughout the study area (proportion of study area)	Median canopy cover (%)	Median canopy bulk density (kg·m^{-3})	Canopy height (m)	Canopy base height (m)
98	Major water bodies (<0.01)				
99	Bare ground, talus, roads, urban areas (0.06)				
102	Grass-dominated areas; mainly valley bottom (0.05)				
144	Shrub-dominated areas interspersed with grasses and trees at low densities; mainly valley bottom and lower slopes (0.08)				
145	Conifer overstory at variable densities with continuous shrub understory; dispersed throughout (0.16)	37	0.09	24	0.6
147	Dense, mature shrubs; predominantly on steeper south and west aspects throughout (0.14)				
163	Mixed conifer stands, moderate surface/ladder fuel loading; extensive throughout (0.23)	67	0.16	21	1.2
165	Dense conifer stands with high surface/ladder fuel loading; predominantly north aspects (0.09)	65	0.16	31	1.2
188	Closed-canopy conifer stands, little or no understory; mainly upper elevations (0.14)	57	0.14	28	6.4
189	Aspen stands, oak stands, and hardwood riparian areas (0.05)	65	0.16	14	2.2

Note: We report median canopy cover and canopy bulk density, as they varied continuously across our study area. Canopy height and canopy base height were fixed for a given fuel model, since it would be inappropriate to use two-dimensional IKONOS imagery to derive vertical vegetation structure. Values were based on sampled field data and were calibrated using an actual wildfire that occurred in the study area following layer development.

Table 2. Weather parameters used in FlamMap conditional burn probability modeling.

Weather parameter	Value	No. of days in sample	Station
Probable maximum 1 min wind speed (km·h^{-1})	40	838	Cashman
Wind direction (of origin) (°)	225	838	Cashman
Fuel moisture (%)			
1 h	1.2	2064	Quincy
10 h	2.1	2064	Quincy
100 h	5.5	2064	Quincy
Live herbaceous	35.4	2064	Quincy
Live woody	60.7	2064	Quincy

Note: Parameters were drawn from the Quincy and Cashman remote automated weather stations and represent the 97th percentile conditions for the predominant fire season in the area (1 June – 30 September).

One approach for implementing a landscape fuel treatment relies on creating defensible fuel profile zones (DFPZs). A DFPZ is an area approximately 0.4–0.8 km wide where surface, ladder, and crown fuel loads are reduced by using a combination of mechanical thinning from below and prescribed fire treatments (USDA 2004*a*). They are usually constructed along roads or ridge tops to reduce fuel continuity across the landscape and provide a defensible zone for fire suppression resources. DFPZs are designed to provide three primary functions: (*i*) provide safe access for firefighters to conduct suppression activities, (*ii*) limit fire behavior to prescribed levels (e.g., limit flame lengths at the 90th percentile weather condition to 122 cm), and (*iii*) create a well-spaced canopy and conditions in which canopy fires are less likely to spread (USDA 2004*a*; Menning and Stephens 2007). DFPZs are generally designed to be used in conjunction with suppression actions including fire line construction, application of aerial retardant, and burnout activities. DFPZs are designed to function under 90th percentile weather conditions and their successful performance has been documented in many instances (Moghaddas and Craggs 2007). Under more extreme weather conditions, DFPZs have

Table 3. Post-treatment modeled conditional burn probability by land allocation in the Meadow Valley analysis area.

	Hectares within analysis area	% of analysis area	Mean burn probability	SD	% change post- minus pre-treatment
Defensible fuel profile zone (DFPZ)	1650	9	0.05	0.06	–62
Group selection (GS)	231	1	0.08	0.07	–36
California spotted owl habitat areas (SOHAs)	194	1	0.22	0.06	–32
California spotted owl protected activity centers (PACs)	1666	9	0.12	0.06	–21
California spotted owl home range core area (HRCA)	2637	14	0.11	0.06	–23
Riparian habitat conservation area (RHCA) (91 m buffer)	1835	10	0.12	0.07	–17
Riparian habitat conservation area (RHCA) (46 m buffer)	285	2	0.10	0.06	–21
Offbase	48	<1	0.03	0.01	+2
Deferred	240	1	0.14	0.03	–22
All other lands	9836	53	0.09	0.07	–20
Analysis area total	18623	100			

reduced fire severity at the stand level, but the performance of DFPZs at the landscape scale in more extreme conditions is less understood (Agee et al. 2000) and has not been systematically studied.

In addition to fuel treatments, a common forest management practice in the Sierra Nevada is group selection (GS) silviculture. In an effort to achieve an all-aged mosaic of timber stands, this uneven-aged regeneration system creates small forest openings by removing all trees in an area up to about 1 ha. These openings are then replanted by hand or naturally regenerated via seed from adjacent stands (USDA 2004*a*). Forest management incorporating GS practices has been applied or proposed in the southern United States (Menzel et al. 2002), boreal Europe, southeast Asia, and California (York et al. 2004). On public lands, trees greater than 76 cm diameter at breast height (DBH) are typically not cut in GS openings.

In this study, we examine the effects of the landscape-level fuel treatment network created by the Meadow Valley Project in the northern Sierra Nevada. This project installed DFPZs and created GS openings to test and demonstrate their effectiveness at meeting a mix of ecologic, social, economic, and fuel reduction objectives. Using high-resolution IKONOS imagery coupled with field measurements, we characterize the fuel and vegetation characteristics in the 18 623 ha Meadow Valley landscape before and after the Meadow Valley Project was implemented. These data were input into the spatially explicit fire behavior models FlamMap and FARSITE (Finney 1998, 2006) to generate estimates of crown fire potential, flame length, and burn probabilities across the Meadow Valley landscape pre- and post-treatment. We summarize results by land allocation type to discern whether certain types are more prone to increased fire behavior and (or) increased probability of burning. FARSITE was further used to simulate a single wildfire occurring under severe fire weather conditions in the Meadow Valley study area. The same ignition and weather conditions were used to simulate this fire for the pre- and post-treatment landscape to demonstrate the influence of fuel treatments on fire size and behavior. This paper addresses the effectiveness of these landscape-scale fuel treatments at reducing modeled fire behavior and provides management considerations pertinent to these results.

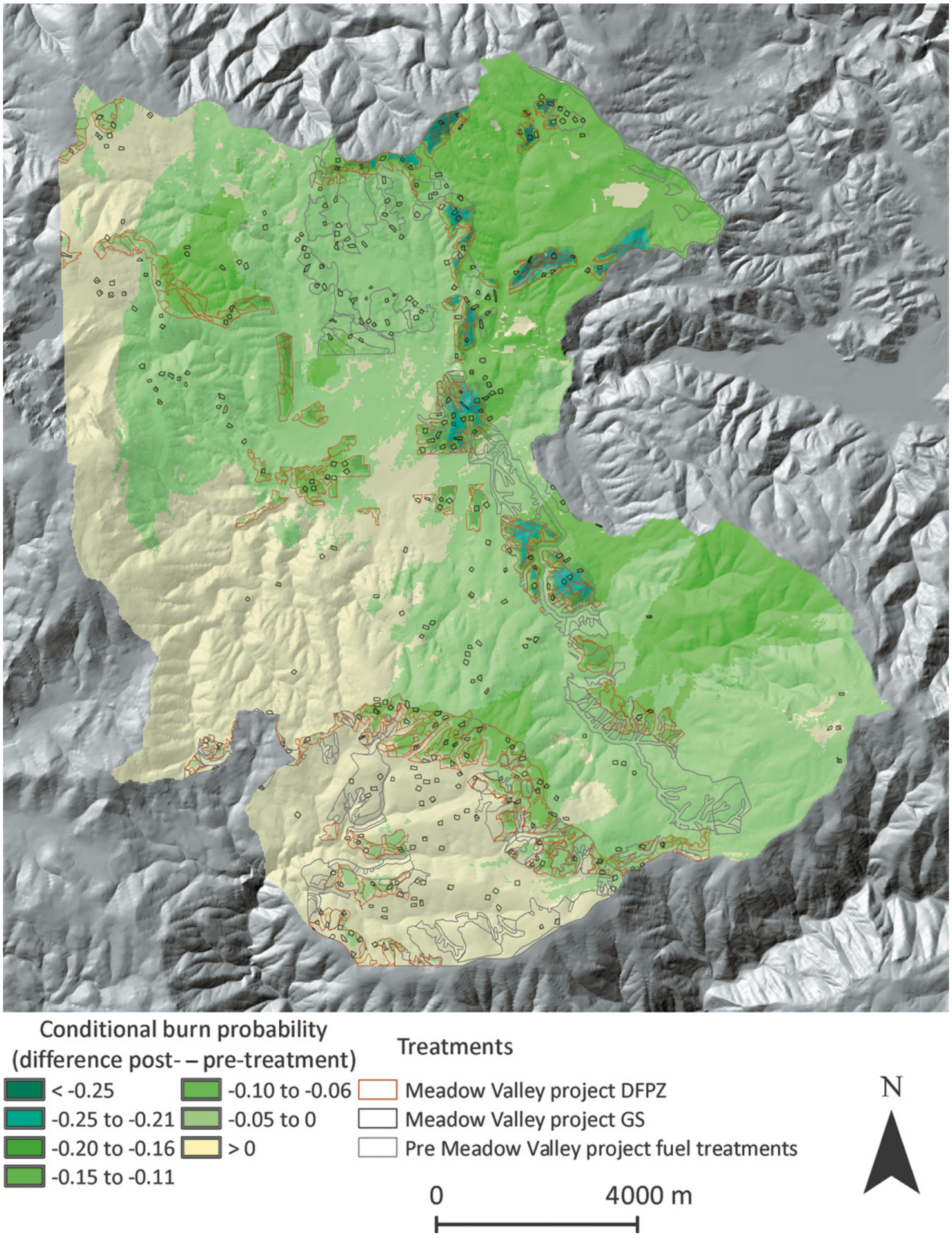
Methods

Study area and land management objectives

The Meadow Valley study area is located in the northern Sierra Nevada range within the Plumas National Forest at 39°56′N, 121°3′W (Fig. 1). The climate is Mediterranean with a predominance of winter precipitation totaling about 1200 mm·year^{-1} (Ansley and Battles 1998). The study area encompasses several subwatersheds totaling 18 623 ha with elevations ranging from 850 to 2100 m (Fig. 1). Although the definition of "landscape scale" can be ambiguous, other landscape-level fire behavior studies in western coniferous forests have analyzed areas ranging from about 16 000 ha (Ager et al. 2007*a*) to 55 000 ha (Finney et al. 2007), which is consistent with the size of the Meadow Valley study area. Vegetation on this landscape is primarily mixed conifer forest (Barbour and Major 1995), a mix of conifers and several hardwoods: white fir (*Abies concolor* (Gord. & Glend.) Lindl. ex Hildebr.), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), sugar pine (*Pinus lambertiana* Dougl.), ponderosa pine (*Pinus ponderosa* P.&C. Lawson), Jeffrey pine (*Pinus jeffreyi* Grev. & Balf.), incense cedar (*Calocedrus decurrens* (Torr.) Florin), and California black oak (*Quercus kelloggii* Newberry). Montane chaparral and some grasslands are interspersed within the forest. Tree density varies by fire and timber management history, elevation, slope, aspect, and edaphic conditions. Fire history, inferred from fire scars recorded in tree rings, suggests a fire regime with predominantly frequent, low-severity fires occurring at intervals ranging from 7 to 12 years (Moody et al. 2006).

This study was conducted within the Meadow Valley Project on USDA Forest Service lands currently managed with DFPZ fuel treatments and GS silviculture. The Meadow Valley Project is included in the Pilot Project of

Fig. 3. Conditional burn probabilities based on 1000 randomly placed ignitions using the Minimum Travel Time function in FlamMap (Finney 2006). Polygon outlines for both defensible fuel profile zone (DFPZ) and group selection (GS) treatments implemented as part of the Meadow Valley coordinated landscape fuel treatment are also identified.



the Herger–Feinstein Quincy Library Group (HFQLG) Act, established to promote ecologic and economic health of designated federal lands (US House of Representatives 1998). Under the HFQLG Act, a range of watershed restoration and forest management activities, including implementation of fuel treatments, GS silviculture, and individual tree selection harvests, have been conducted to meet these objectives. Individual tree selection was not implemented in the Meadow Valley Project.

Landscape fuel treatments

Beginning in the late 1990s, the Plumas National Forest initiated several fuel reduction projects within the study area. Several treatments predate our vegetation and fuel data collection. These prior treatments account for a total of 9% of the study area and are included in the pre-treatment condition of this analysis. The Meadow Valley Project, which began implementation in 2005, was designed in part to create a landscape-level fuel reduction network that

Table 4. Fire type by land allocation in the post-treatment Meadow Valley analysis area.

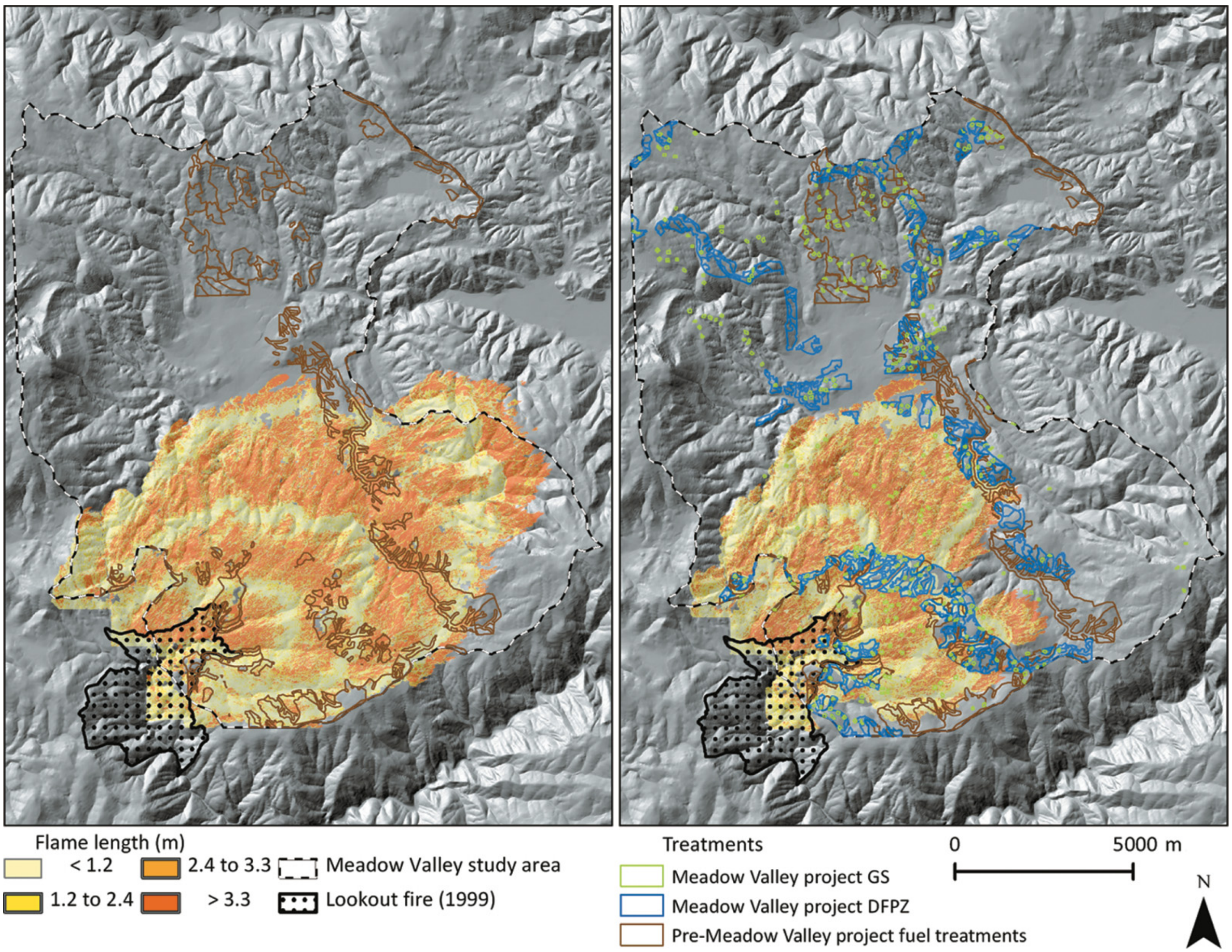
	Treated lands		Untreated lands							
Fire type	All DFPZs and prior fuel treatments (%)	Group selection (GS) (%)	California spotted owl habitat areas (SOHAs) (%)	California spotted owl protected activity centers (PACs) (%)	California spotted owl home range core area (HRCA) (%)	Riparian habitat conservation area (46 m buffer) (%)	Riparian habitat conservation area (91 m buffer) (%)	Deferred (%)	Offbase (%)	All other lands (%)
Nonburnable (no fire)	5	0	2	2	2	5	13	3	10	9
Surface	71	2	31	47	48	48	40	51	29	48
Passive crown	15	98	4	21	19	30	34	6	39	23
Active crown	9	0	62	31	31	17	13	40	22	20

linked these prior treatments with an additional 1650 ha of DFPZs. Within DFPZs, surface, ladder, and crown fuels were reduced. Conifers and hardwoods up to 51 cm DBH were thinned from below, using a whole-tree harvest system, to a residual canopy cover of 40%. Where DFPZs fell within the wildland–urban interface, the upper DBH limit for harvest was 76 cm (USDA 2004*a*). Post-harvest treatments to reduce and rearrange surface fuels included grapple piling, hand piling, pile burning, and underburning. In addition to DFPZs, 231 ha of GS was implemented as part of the Meadow Valley Project, in accordance with the HFQLG Act. GS treatments included removal of all conifers up to 76 cm DBH, with individual GS units ranging from 0.25 to 1 ha in size. Site preparation consisted of mechanical grapple piling and burning. GS units were allowed to regenerate naturally or planted to a density of 270 trees·ha^{-1} with a mix of sugar pine, ponderosa pine, and Douglas-fir (USDA 2004*a*). The post-treatment condition for this analysis reflects the complete implementation of the Meadow Valley Project, including harvest, surface and activity fuel treatments, site preparation, and planting. Including the prior fuel treatments, a total of 19% of the study area was treated at the time of the post-treatment analysis.

Land allocation delineations

The Meadow Valley study area was divided into 11 land allocations, each generally associated with predefined management direction, standards, and guidelines (USDA 2004*b*) (Fig. 2). These land allocations, in part, dictated fuel treatment type, scale, and location (USDA 2004*a*) and were based on the management direction for the HFQLG Pilot Project area (USDA 2004*b*). Deferred and offbase lands were effectively set aside as reserve areas where no DFPZ construction, timber harvest, or road construction can occur during the HFQLG Pilot Project. Likewise, DFPZ construction and timber harvest were excluded from spotted owl habitat areas (SOHA) and protected activity centers (PAC) to limit potential impacts to the California spotted owl. Home range core areas (HRCA), which average about 300 ha around each PAC, were also largely excluded from treatment activities in the Meadow Valley Project. In addition, the Meadow Valley project predominantly excluded all riparian habitat conservation area (RHCA) or stream buffers intended to protect riparian and aquatic resources. Fish-bearing streams and non-fish-bearing perennial watercourses were buffered 91 and 46 m from each bank, respectively. Prescribed fire and hand thinning was allowed within these RHCA buffers, but mechanical operations were chiefly excluded. Fuel treatments were also largely excluded from intermittent and ephemeral watercourse buffers. Each of these land allocations has placed limitations on DFPZ construction or the treatment prescriptions within the Meadow Valley landscape (USDA 2004*a*, 2004*b*). In addition to the described land allocations, areas were additionally delineated as treated with DFPZ, GS, or prior fuel treatments. We obtained geographic information system (GIS) files for each of these allocations from the Plumas National Forest corporate database and staff. Areas not falling in one of the previously mentioned land allocation types were classified as "all other lands" (Fig. 2). Land allocation types were compiled as mutually exclusive categories in one layer preventing overlap

Fig. 4. Modeled area burned classified into flame length categories based on a single "problem fire" scenario. This scenario consisted of an ignition on the southwest edge of the landscape (for which we used an actual fire that occurred in 1999) burning under fairly severe conditions. This problem fire was simulated using FARSITE for the pre- (left) and post-treatment (right) Meadow Valley landscapes. Polygon outlines for both defensible fuel profile zone (DFPZ) and group selection (GS) treatments implemented as part of the Meadow Valley coordinated landscape fuel treatment are also identified.



among the individual types so that summed area among the types was not greater than the total study area. Where the land allocations overlapped, we used the hierarchy as follows: (1) DFPZ/GS, (2) RHCA, (3) HRCA/PAC, (4) SOHA, and (5) offbase/deferred.

Imagery

We acquired high-resolution IKONOS imagery for the study area from the Space Imaging Corporation in 2003 and 2004; the acquisition was spread over 2 years due to incomplete coverage of the study area in 2003. The imagery captured the pre-Meadow Valley treatment condition but included completed fuel treatments implemented prior to the Meadow Valley Project. The prescribed acquisition was intended to be near the summer solstice at noon to ensure minimal topographic and tree shadowing. The 2003 imagery was collected on 30 June. Due to poor weather and other constraints, 2004 image acquisition was delayed until 3 September. Both acquisitions had identical prescriptions: 1 m panchromatic and 4 m multispectral imagery collected with an upgraded and narrowed field of view (72–90° from azimuth). We completed radiometric corrections to minimize backscatter and distortion due to atmospheric moisture and haze. These radiometrically corrected images were then orthorectified using the Geomatica 9.1 Orthoengine module using 12 independent ground reference points.

Creating fuel layers

Pre-treatment vegetation and fuel characteristics were mapped from the IKONOS mosaic using supervised classification (Menning 2003). We created the five vegetation/fuel layers needed to run the spatial fire models FARSITE (Finney 1998) and FlamMap (Finney 2006): fuel model, canopy cover, canopy base height, canopy height, and canopy bulk density. We used vegetation spectral signatures to classify the IKONOS imagery into 10 discrete vegetation and fuel classes (Table 1). Based on the stand structure and fuel characteristics observed in the field and sampled in

Table 5. Characteristics of a modeled “problem fire” for the pre- and post-treatment Meadow Valley landscape.

Treatment phase	Fire size (ha)	Average F_L (m) (SD)	Area burned by flame length class (proportion)			Modeled problem fire area intersecting treatments (ha) (proportion)		
			F_L < 2.4 m (SD)	2.4 m < F_L < 3.4 m (SD)	F_L > 3.4 m (SD)	DFPZ	GS	Prior fuel treatments
Pre-	9176	3.1 (3.3)	2511 (0.27)	3772 (0.41)	2893 (0.31)			1175 (0.13)
Post-	5569	2.7 (3.0)	2075 (0.37)	2075 (0.37)	1546 (0.28)	809 (0.15)	100 (0.02)	1024 (0.18)

Note: Area burned is summarized using two flame length (F_L) break values. These F_L values are based on operational constraints for fire suppression activities. The area intersecting treatments includes defensible fuel profile zone (DFPZ) and group selection (GS) units that were both burned over by the modeled fire and immediately adjacent to the fire perimeter. For both F_L classes and the area intersecting treatments, we also report the proportion of the final fire size represented in the respective classes.

field plots for each class, we assigned initial fuel models to best match surface fuel structural characteristics described in Scott and Burgan (2005). We used expertise of local and regional fire managers to aid in fuel model selection. Supervised classification of vegetation and fuel models was completed in Erdas Imagine 9.0. Training sites were chosen using the high-resolution panchromatic imagery as well as the multispectral IKONOS mosaic. Between five and 10 training sites were chosen for each class (Table 1) with emphasis on minimal intermixing of other vegetation types in the training sample.

Canopy cover was linked to the vegetation and fuel type (Table 1). Under an individual tree, canopy cover, by definition, is very high. Canopy cover drops as multiple trees in an area are considered and the gaps between them expose the ground. Hence, we applied a high canopy cover value, 90%, to forest vegetation types. To accept these values in a fine-grain mosaic would be problematic, however. To create a more realistic set of continuous values for the canopy cover, we smoothed the canopy cover values (7 × 7 pixel FAV filter, PCI Geomatica). The resulting canopy cover across the landscape ranges from zero, where no trees are classified, to 90% for pure, almost completely overlapping stands that occasionally occurred on northern aspects. As a result of the smoothing, however, patches of forest usually average a more realistic and variable 30%–80% canopy cover depending on tree density. Predictably, the densest stands grow on northern aspects and this is where the canopy cover is highest.

Canopy height and crown base height were assigned as set values for each vegetation and fuel class (Table 1). These values were based on plot-level data from 72 field monitoring plots within the study area (C. Dillingham, Plumas National Forest, personal communication, (2009)). Tree information from these field plots was input to the Forest Vegetation Simulator (FVS) to generate stand-level estimates of canopy top height and canopy base height for each vegetation and fuel class. Within the FVS, canopy fuel characteristics, including stand-level canopy base height and canopy bulk density, are calculated as described in Scott and Reinhardt (2001). As we were unable to differentiate different species of conifers from the IKONOS imagery, we assigned an initial canopy bulk density to each vegetation class. Values for canopy bulk density within a particular vegetation class were then scaled to canopy cover using previously published values for mixed conifer forests (Scott and Reinhardt 2005).

Calibrating fuel layers

We were fortunate to have an actual wildfire burn largely within our IKONOS mosaic image following the acquisition dates. The Rich fire, which started 29 July 2008 and was contained 11 days later, burned 2590 ha just north of our study area (Fig. 1). This provided an excellent opportunity to calibrate our vegetation and fuel layers. Through multiple iterations, we adjusted not only fuel model assignments but canopy height and canopy base height values as well. We used the range of variability within the canopy height and canopy base height values for the FVS compiled stands mentioned earlier as a basis for modifying these values. Fuel models remained in the same vegetation series but the new model was iterated by one level within a given fuel model group (i.e., from model 163 to 165) (Scott and Burgan 2005). The intent of these adjustments was to reasonably approximate the size and post-fire effects observed for the Rich fire using the fire models FARSITE (Finney 1998) and FlamMap (Finney 2006). Our initial fuel model and canopy layers substantially underpredicted fire spread and crown fire activity. Our final iteration resulted in approximately 80% agreement between the modeled and actual fire size. This agreement suggests reasonable validity with respect to our ability to model fire over the Meadow Valley landscape.

Post-treatment adjustments

Post-treatment adjustments were made for each of the five layers developed for spatial fire modeling: fuel model, canopy cover, canopy base height, canopy height, and canopy bulk density. These adjustments were applied only to those raster cells that were within Meadow Valley Project treatment polygons. These reflect the actual treatment boundaries implemented on the ground. The treatment polygons differed slightly from the areas mapped in the Meadow Valley Project environmental planning documents, as units were removed or modified during implementation due to limited access, steep slopes, or other constraints. Modified values for the four canopy layers were based on post-treatment field data collected within the analysis area 1 year following implementation. As with the pre-treatment plot-level data, the post-treatment plot data were run in FVS to compute not only canopy height and canopy base height but canopy cover and canopy bulk density as well. Plot-level values were averaged to generate stand-level estimates. These estimates were stratified by treatment type (DFPZ, GS), conifer and nonconifer vegetation type, and geographic area. Where post-treatment data were available for multiple stands within a given treatment type stratum, we randomly assigned the stand-level values for the four canopy parameters to treated stands using ArcGIS to capture the full range of variability that actually exists post-treatment. Post-treatment fuel models were assumed to be light- to moderate-load timber litter (FM 181) for DFPZ conifer stands based on activity fuel treatments, which include prescribed underburning or piling and burning (Scott and Burgan 2005). Nonconifer DFPZ stands, which were primarily shrub vegetation and fuel types, were assigned a moderate-load shrub fuel model (FM 142) based on characteristics observed in the field.

Fire weather: conditional burn probability and fire type modeling

Weather data were drawn from the Quincy and Cashman remote automated weather stations (RAWS) (Fig. 1). The Quincy RAWS had a longer period of record (since 1991), and as such, we used the Quincy data for determining fuel moistures. We used the Cashman RAWS for data on wind speeds and directions. The Quincy RAWS would be more ideal given the shorter period of record for Cashman (online since 2002); however, local fire managers and weather experts indicated that wind speeds recorded by the Quincy RAWS are well below those experienced in the study area. We adjusted the Cashman RAWS wind speeds for probable maximum 1 min speed using recommendations outlined by Crosby and Chandler (2004). These adjusted wind speeds resulted in better agreement between observed crowning in the 2008 Rich fire and our modeled crown fire potential for the calibration. We used 97th percentile fuel moisture and wind speed values for our analysis (Table 2), as these are the conditions that support large fire growth. We used the program Fire Family Plus (Main et al. 1990) to calculate fuel moistures and wind speeds, limiting our analysis period to the predominant fire season for the study area landscape (1 June – 30 September).

The wind direction that we used for modeling fire was determined by identifying the direction that consistently showed the highest average wind speed for the 1 June – 30 September analysis period. Seventy percent of all wind speed observations that were at or above the 90th percentile value were from one direction, southwest (225°). We used this direction and the adjusted 97th percentile wind speed, along with a 10 m digital elevation model for our study area, to develop gridded winds (or "wind vectors") using the program Wind Ninja (Butler et al. 2006).

Fire modeling

We use the Minimum Travel Time algorithm in FlamMap (Finney 2006) to derive conditional burn probability estimates based on 1000 random ignitions for both the pre- and post-treatment landscapes. This methodology has been utilized in other previously published papers (Ager et al. 2007*b*; Finney et al. 2007). The maximum simulation time for each ignition was 900 min, or three 5 h burning periods, with a node resolution for fire behavior computations of 30 m. All raster layers were resampled to 10 m pixel resolution to increase computational efficiency. Simulation times were 7.4 and 5.8 h for pre- and post-treatment model runs, respectively, using a four-processor, 4 GB RAM machine. We buffered our study area by 2 km where possible and then extracted conditional burn probability estimates for the analysis area (not including the buffer, see Fig. 1). FlamMap was also used to generate fire type for the pre- and post-treatment landscapes.

We used FARSITE to simulate the potential fire behavior and size of a single "problem fire" (sensu Bahro et al. 2007) ignited on the upwind edge of the study area in both the pre- and post-treatment landscapes. A "problem fire" is defined as a "hypothetical wildfire that could be expected to burn in an area that would have severe or uncharacteristic effects or result in unacceptable consequences" (Bahro et al. 2007). We used a line ignition for this simulation based on an actual 1999 fire that occurred in the study area (Lookout Fire), which, if burning under dry fuel moisture conditions and moderate to high southwest winds, would pose significant fire management difficulties within the Meadow Valley study area (Fig. 1). We modeled this supposed problem fire for 3 days under the same conditions that existed during the previously mentioned Rich fire. We used the weather observed during the Rich fire, as opposed to basing the weather on percentiles, because it better reflected actual temporal variability (hourly and diurnal) experienced throughout an active period of fire growth. The Rich fire, which burned just north of the Meadow Valley study area, demonstrated substantial growth during the first 2 days (48 h), and as such, suppression efforts were less effective on fire growth during this time (USDA 2008). We used the same ignition and weather conditions to simulate a fire on the pre- and post-treatment landscapes to examine the effectiveness of the DFPZ network under this theoretical problem fire scenario. We summarize area burned for these simulated fires by three flame length classes, which correspond to different tactical approaches for fire suppression efforts. Theoretical fire suppression was not incorporated in any fire modeling analyses.

Results

Conditional burn probability

Average conditional burn probability across all land allocations in the study area was 0.13 (SD 0.09) and 0.10 (SD 0.07) for pre- and post-treatment landscapes, respectively. These estimates are "conditional" in that they represent the probability of a fire burning in a given pixel provided there is an ignition within the buffered study area (Fig. 1). Average pixel-to-pixel difference (post- minus pre-treatment) was –0.03 (SD 0.04). Within DFPZ treatments, overall conditional burn probabilities were decreased by 62% relative to pre-treatment values. In GS openings, this relative decrease was 36% following treatment. The only increase (2%) occurred in offbase areas, which are managed as reserve areas off limits to fuel treatment. Probabilities decreased in all other untreated areas, with relative declines ranging from 17% in the widest RHCA stream buffers to 32% in SOHA areas reserved for spotted owl management (Table 3).

Figure 3 maps the pixel-to-pixel change in burn probability following DFPZ and GS treatments. Across the Meadow Valley study area, the reduction in burn probability becomes more pronounced from the southwest to the northeast, or moving from upwind to downwind. In addition, shadows of reduced burn probability on the lee side (northeast) of DFPZs can be seen in untreated areas.

Crown fire potential

Under modeled conditions for the post-treatment environment, about half of the untreated areas remained prone to passive and active crown fire. Table 4 displays the proportion of each land allocation that is likely to burn under passive crown fire, active crown fire, or surface fire conditions. The combined DFPZs and prior fuel treatments show the lowest potential for crown fire. GS openings had virtually no vulnerability to active crown fire, but 98% are prone to passive crown fire. Among untreated areas, the highest proportions of crown fire potential were observed in lands managed for spotted owl (SOHA, PAC, HRCA).

Problem fire scenario: size and behavior

In the problem fire scenario, modeling the treated landscape reduced fire growth, and therefore final fire size, by 39% compared with the pre-treatment condition (Fig. 4; Table 5). Overall average flame length was lower throughout the problem fire in the post-treatment landscape (Table 5). In the post-treatment fire scenario, more than one third of the fire area burned at flame lengths less than 2.4 m. While the proportions of the pre- and post-treatment fire burning with flame lengths exceeding 3.4 m were very similar (0.31 and 0.28, respectively), the post-treatment fire had nearly 1350 fewer hectares under such high fire intensity and extreme suppression conditions. On the post-treatment landscape, the modeled problem fire intersected a combined total of 1833 ha of DFPZs and prior fuel treatments (Table 5).

Discussion

Conditional burn probability

In this study, the landscape-scale network of DFPZs and prior fuel treatments were effective at reducing conditional burn probabilities across all land allocation types except the small area of offbase lands. Burn probabilities are related to fire size, i.e., higher burn probabilities over a landscape are indicative of the potential for larger fires (Finney et al. 2007; Seli et al. 2008). As such, it is clear that the pre-treatment landscape is more conducive to large fire growth relative to the post-treatment landscape. While the influence of the treatments on burn probabilities of each land allocation varied, the untreated stands designated for management of spotted owls (SOHA, PAC, HRCA), riparian and aquatic resources (RHCA), and future reserve lands (deferred), as well as the remaining private and unclassified lands, all benefited from the landscape fuel treatments. The shadow of reduced conditional burn probability on the lee, or northeast, side of the DFPZs reflects the influence of both the fuel treatment and the prevailing southwest winds in this landscape. A similar shadow of reduced burn severity immediately adjacent to treated areas has been reported for fires across the western United States (Finney et al. 2003, 2005). Areas not immediately adjacent to treated areas experienced a reduction in burn probability as well, particularly in areas on the northeastern portion of the landscape, which were downwind of several DFPZs. Fires burning from the southwest would be more likely to encounter modified fuels in DFPZs in their progression toward the northeast. While these results demonstrate that fuel treatments can modify conditional burn probabilities outside treated areas, reduced burn probabilities do not necessarily reflect reduced fire behavior or severity characteristics if the untreated areas do indeed burn.

Crown fire potential

The large reduction in the potential for both passive and active crown fire within DFPZs is consistent with other published studies (Strom and Fulé 2007; Stephens et al. 2009). While fuel treatments were effective at reducing burn probabilities outside treated areas, they did not influence crown fire potential in untreated areas. Areas managed for spotted owl (SOHA, PAC, HRCA) typically support relatively high stand density and canopy cover levels, which remain prone to a high proportion of crown fire. Unfortunately, high-severity fires within untreated reserve areas may negatively impact the very values they were created to protect, such as high stand density, canopy cover, and large trees (Spies et al. 2006) and water resources. With the prevalence of high-severity fire generally increasing in forests of the Sierra Nevada (Miller et al. 2009) and western United States, these findings emphasize the critical need to address the potential for high-severity fire in areas where fuel treatments are being excluded (Spies et al. 2006).

The finding that nearly all GS treatments were susceptible to passive crown fire was not surprising. These forest openings comprise young regenerating trees, typically less than 1 m tall. Although surface fuel loads in GS units were generally low, the very low crowns were prone to torching because they were so close to the ground. These stands are expected to remain susceptible to passive crown fire for approximately 20 years (Stephens and Moghaddas 2005), depending on site and growth conditions. This susceptibility can be mitigated by initially planting groups at a relatively low density, reducing shrubs and ladder fuel using intermittent treatments, using whole-tree harvesting to reduce overall stand density, and using prescribed burning (Kobziar et al. 2009; Stephens et al. 2009).

Problem fire scenario

Based on the problem fires simulated on the pre- and post-treatment landscapes, the Meadow Valley Project effectively enhanced existing fuel treatments by, in part, providing continuity between them. Based on the final post-treatment fire perimeter (Fig. 4), 33% of the modeled burned area intersected either Meadow Valley Project DFPZs or prior fuel treatments (Table 5). In combination, these treatments substantially reduced overall modeled fire size when compared with the pre-Meadow Valley Project landscape (Table 5). In the pre-treatment condition, the problem fire scenario burned about 9000 ha, or 50%, of the study area. As with actual problem fires, the area burned covered multiple subwatersheds and forested stands across a broad range of vegetation types. As a result of the additional DFPZ fuel treatments, the post-treatment scenario effectively reduced the problem fire size to about 30% of the study area. These results suggest that the Meadow Valley Project met its objective to link several existing fuel treatments and ultimately create a network of quasi-linear treatments across the Meadow Valley landscape (USDA 2004*a*).

Although the effects of fire suppression were not modeled for the problem fire scenarios, potential suppression tactics and related fire behavior can be inferred from the model outputs using the Fireline Handbook Haul Chart (National Wild-fire Coordinating Group 2006, appendix B). More than a third of the post-treatment problem fire burned with flame lengths <2.4 m. This generally represents conditions that can be controlled with suppression forces using hand tools (where flame lengths generally do not exceed 1.2 m) and equipment such as dozers, engines, and retardant aircraft. Where flame lengths exceed 3.4 m, crowning, spotting, and major runs become common and control efforts at the head are often ineffective. Although close to a third of both the pre- and post-treatment problem fire area burned with these greater flame lengths, the post-treatment landscape contained about 1350 fewer hectares burning under these conditions. This suggests that the fuel treatments may result in a problem fire with a reduced extent of suppression challenges and greater potential for suppression effectiveness, which could further reduce the final fire size.

The substantial reduction in both total area and area burned at higher flame lengths under the post-treatment problem fire scenario was notable given only 20% of the study area had been treated (Table 5). Both the orientation of the treatments, which was approximately orthogonal to the predominant wind direction throughout the duration of the simulated problem fire, and the long, continuous shape of the DFPZs likely resulted in the problem fire intersecting fuel treatments in several places. In combination, these factors limited the ability of the simulated fire to circumvent treated areas. This impact of treatment orientation and shape relative to the dominant modeled wind direction is also evident in the conditional burn probability analysis (Fig. 3), which demonstrates a gradient of increasing treatment effectiveness trending towards the downwind portion of the landscape. Given that 70% of the wind observations at or above the 90th percentile wind speed value come from the modeled direction (225°), the results indicate that the Meadow Valley treatments may be well situated to reduce potential fire behavior for a majority of the problematic winds experienced in the study area. In addition to the angle of treatment orientation, the "layered" arrangement of the treatments may also have contributed to the reduced fire spread (Fig. 4). This arrangement may have resulted in a "speed bump" type reduction in fire spread (Finney 2001) where the fire intersected and was slowed by the first set of treatments, and before it could fully regain momentum, the fire intersected another layer or row of treatments (Fig. 4). It is important to emphasize that we did not model suppression, primarily because of the challenge of obtaining accurate spatial information on operations and the difficulty in modeling suppression impacts. Taking suppression actions into account, which is part of the DFPZ strategy, modeled post-treatment fire sizes could be even more reduced relative to pre-treatment.

Acknowledgement is given to the fact that the fuel and fire behavior models used in this assessment are simplified representatives of real fuel conditions (Burgan and Scott 2005) and fire behavior (Pastor et al. 2003; Stephens et al. 2009). Further, the models have not all been field validated because of the difficulty of doing so (Scott and Reinhardt 2001). Crown fire behavior is notably complex and is controlled by several interacting, highly variable elements such as weather, crown characteristics, and surface fuels, which the models tend to homogenize. However, these models still represent the best available compilation of fire behavior science, whether empirically or theoretically derived (Pastor et al. 2003), and therefore, results of modeled fire behavior can be particularly useful for relative comparisons between treated and untreated landscapes.

Implications for management

It is virtually impossible to exclude fire from most fire-prone landscapes, such as found across the western United States, over long periods of time (Reinhardt et al. 2008). During extreme weather conditions, suppression efforts can become overwhelmed and fires can cover very large areas. Even under less extreme weather conditions, where fuel and forest structure conditions render large, relatively homogenous tracts of forests prone to high-intensity burning, suppression efforts can be rendered ineffective. This may be particularly true as the effects of climate change are manifested on fire severity trends (Millar et al. 2007; Miller et al. 2009). Analysis of our data supports the assertion that "no treatment" or "passive management" (Agee 2002; Stephens and Ruth 2005) perpetuates the potential for exacerbated fire behavior in forests similar to those in this study. Our results demonstrate that treating a portion of the landscape can result in a decrease in probability of areas outside those treated areas being burned (Finney et al. 2007). While this suggests that coordinated landscape fuel treatments can reduce burn probability, even given a moderate proportion of area that cannot be treated due to management constraints (Collins et al. 2010), the untreated areas are still prone to burning with high severity (Table 4). In many cases, lands with designated management emphasis, such as habitat areas and stream buffers, are distributed throughout and across the landscape. Creating fuel treatments that exclude these and other land allocations can result in a patchwork of treated area heavily dissected with, for example, untreated stream buffers. The untreated areas may benefit from reduced burn probabilities as a result of the fuel treatments, but they will remain vulnerable to the effects of high-severity wildfire (Safford et al. 2009). Where ecologically sound and legally feasible, managers should consider treating these important and potentially sensitive land allocations. When left untreated, wildfire may continue to threaten the same ecological, social, or historic resource values that the allocations were designed to conserve.

These results indicate effective reduction in conditional burn probability at approximately 20% of the landscape treated and where approximately 33% the area of an individual modeled problem fire perimeter intersects treated areas. Findings from the problem fire modeling scenario suggest that the DFPZ and fuel treatments in the Meadow Valley study area were well situated on the landscape. In determining fuel treatment alternatives, managers must consider the size, shape, and placement of treatments relative to fuels, topography, access, and prevailing weather patterns.

Conclusion

Across the western United States, the incidence of reduced fire severity within fuel treatments has been repeatedly documented under both modeled (Stephens et al. 2009) and real wildfire conditions (Moghaddas and Craggs 2007; Ritchie et al. 2007; Safford et al. 2009). The Meadow Valley Project treatments, in conjunction with existing fuel treatments within the analysis area, reduced conditional burn probability and potential fire spread at the landscape level. If climate change continues, even based on conservative projections, it is likely that coniferous forests in the Sierra Nevada will experience longer fire seasons (Westerling et al. 2006), which are relatively drier and more conducive to high-intensity fire (Miller et al. 2009). To reduce this hazard, there is not one fuel treatment strategy. Rather, a combination of strategies is needed, especially when dealing with complex landscapes and management objectives (Stephens et al. 2010). These treatments include those mechanical and prescribed fire treatments that utilize the basic principles of fuel reduction (Agee and Skinner 2005), including a combination of surface, ladder, and crown fuel reduction achieved by combining thinning from below with prescribed fire treatments. Where wildland fire use is a viable management option, further research is needed on the integration of fuel treatments and wildland fire use as a fuel management strategy, particularly to reduce fire hazard in more sensitive land allocation types. At a landscape scale, this is a difficult proposal and will likely challenge many of the current paradigms within forest policy, air quality regulations, fire management, and environmental analysis, documentation, and decision making (Germain et al. 2001; Collins et al. 2010).

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