Environmental Management (2016) 57:516–530
DOI 10.1007/s00267-015-0632-8

RESEARCH

Incorporating Resource Protection Constraints in an Analysis of Landscape Fuel-Treatment Effectiveness in the Northern Sierra Nevada, CA, USA

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Received: 13 January 2015 / Accepted: 17 November 2015 / Published online: 27 November 2015

Abstract Finding novel ways to plan and implement landscape-level forest treatments that protect sensitive wildlife and other key ecosystem components, while also reducing the risk of large-scale, high-severity fires, can prove to be difficult. We examined alternative approaches to landscape-scale fuel-treatment design for the same landscape. These approaches included two different treatment scenarios generated from an optimization algorithm that reduces modeled fire spread across the landscape, one with resource-protection constrains and one without the same. We also included a treatment scenario that was the actual fuel-treatment network implemented, as well as a no-treatment scenario. For all the four scenarios, we modeled hazardous fire potential based on conditional burn probabilities, and projected fire emissions. Results demonstrate that in all the three active treatment scenarios, hazardous fire potential, fire area, and emissions were reduced by approximately 50 % relative to the untreated condition. Results depict that incorporation of constraints is more effective at reducing modeled fire outputs, possibly due to the greater aggregation of treatments, creating greater continuity of fuel-treatment blocks across the landscape. The implementation of fuel-treatment networks using different planning techniques that incorporate real-world constraints can reduce the risk of large problematic fires, allow for landscape-level heterogeneity that can provide necessary ecosystem services, create mixed forest stand structures on a landscape, and promote resilience in the uncertain future of climate change.

Keywords Treatment optimization · Burn probability · Emissions · Fuel treatments · Mixed conifer

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Introduction

Following the impacts of the third largest wildland fire in California state history (Rim Fire 2013), as well as other recent large wildfires occurring in the Sierra Nevada (e.g., Storrie Fire 2002, Moonlight Fire 2007, Chips Fire 2012, King Fire 2014), developing forest land-management plans that retain diverse forest structure, decrease loss due to large-scale, high-severity fires, and increase resiliency for the uncertainty that climate change presents is a high priority on public land. Past forest management practices, as well as the exclusion of fire from a landscape with adaptations for resilience and recovery after low-to-mixed severity fires, have left large, contiguous areas of the Sierra Nevada, as well as other frequent fire-adapted forest types uncharacteristically overstocked and susceptible to large and intense wildfire (Hessburg et al. 2005; Miller et al. 2009; Stephens et al. 2009). However, finding novel ways to plan and implement landscape-level forest treatments that protect sensitive wildlife and other key ecosystem components, while also reducing the risk of large-scale, high-severity fire, is difficult.

The Sierra Nevada mixed conifer forest ecosystem, historically composed of primarily large, old, widely spaced trees (Collins et al. 2014; Stephens et al. 2015), is now characterized by large areas at the stand level that are fairly uniform (McKelvey and Johnston 1992; Verner et al. 1992), or classified as single cohort (Oliver and Larson 1996). This type change, due to past management practices, has resulted in a much greater density in the understory consisting of shade-tolerant conifers, such as incense-cedar (*Calocedrus decurrens*) and white fir (*Abies concolor)* (Ferrell 1996), which can develop for several decades as a single cohort following a disturbance (Oliver and Larson 1996). This increase in shade-tolerant species in the middle and lower canopies has reduced the amount of shade-intolerant regeneration, except in areas opened by wildfire or management (Verner et al. 1992; Weatherspoon et al. 1992). In addition to the ingrowth of shade-tolerant species, forest floor fuels, snags, and coarse woody debris have accumulated beyond historical levels, which is likely to increase the risk of fire propagation by spotting and increases in suppression difficulty (Verner et al. 1992; Weatherspoon et al. 1992).

Coupled with these structural and compositional changes in dry forest types, there is considerable uncertainty that land managers face concerning the effects of global climate change (Moritz et al. 2012). The seasonally dry, mixed conifer forests of California, which historically burned at shorter return intervals than found recently (Stephens et al. 2007; Van de Water and Safford 2011), are less susceptible to high-severity fire following implementation of mechanical fuel/restoration treatments (Stevens et al. 2014; Hurteau et al. 2011; Stephens et al. 2012a). However, restoring all of the Sierra Nevada forests with mechanical treatments is not feasible due to the large spatial scale of the problem, steep topography, and concerns on impacts of treatments to certain resources (North et al. 2012).

Changes due to fire suppression in some forests have possibly contributed to an increase in spotted owl habitat with greater stand densities, greater development of middle and lower canopy layers, more snags, and more coarse woody debris (Verner et al. 1992; Weatherspoon et al. 1992; Spies et al. 2006), but there is a tradeoff with the increases in habitat. Limitations due to operational constraints such as wildlife Protected Activity Centers (PACs), California spotted owl (*Strix occidentalis occidentalis*) habitat, Northern Goshawk (*Accipiter gentilis*) habitat, slope, road access and feasibility, make planning for landscape-level treatments difficult (Collins et al. 2010). The factors that create ideal forest composition for protected wildlife can also contribute to the risk of large, high-severity fires and the negative effects following high mortality events (Verner et al. 1992; Weatherspoon et al. 1992; Saspis et al. 1996).

It has also become necessary to not only quantify the loss or gain of habitat in these denser forests, but to also account for the emissions and carbon loss that is associated with low, mixed and high-severity fires. Following the passage of the State of California Global Warming Solutions Act of 2006 (AB32), and the mandatory state inventory of green house gas (GHG) emissions and removals by forests, grasslands, wetlands, and other natural lands (Lydersen et al. 2014), the California Air Resources Board (ARB) was tasked with development of a program that quantified GHG emissions from wildfire. This program has allowed the state of California to assess GHG emissions of large- and small-scale wildfires throughout the state.

Given the effects of fire suppression, carbon stocks in some California forests that once burned with greater frequency have increased (Collins et al. 2011). The greater carbon stocks that are associated with the ingrowth of mid- and lower-canopy trees as well as the increasing wildfire frequency and severity combined to result in the release of higher emission over time from both direct and indirect sources (North et al. 2009a). Indirect emissions from wildfire, through the decomposition of fire-killed trees, have been reported to be as much as three times the carbon output lost during a wildfire (Auclair and Carter 1993) and can continue to release carbon into the atmosphere for a number of years (Dore et al. 2008; Meigs et al. 2009). However, it is also important to note that once treated, forests may also store a greater amount of carbon with understory removal and large-diameter tree growth (Stephens et al. 2009, 2012c; North et al. 2009a; Collins et al. 2014) than is currently stored in overstocked forest structures. The idea of understory removal, or thinning, as an effective process for increasing the stored carbon of residual trees is not limited to the forests typified by the fire-adapted Sierra Nevada. Studies in the Southern Appalachian mixed hardwoods demonstrate evidence for greater aboveground live-tree carbon in thinned versus unthinned stands (Keyser and Zamoch 2012). In the north east, it is suggested by the North East State Foresters Association (2002) that "management strategies that encourage larger trees, employ harvest methods that reduce waste and damage to residual trees, and minimize soil disturbance during harvest all improve carbon sequestration activities." Additional information for the working forests recommended appropriate thinning regimes that concentrate growth on fewer, larger trees (Perschel et al. 2007).

This suggests that forest treatments can reduce the release of direct emissions during and immediately following wildfire, decrease the net release of emissions from tree mortality over a longer period, and increase aboveground live-tree carbon from forest thinning. Decreases in emissions associated with forest fuel hazard treatments have been noted in thinning treatments following fire, as well as decreasing the vulnerability of live-tree carbon to the associated release of emissions following mortality

(Stephens et al. 2012b). However, fully implemented landscape fuel-treatment networks are rare in the western U.S (Stephens et al. 2014). This may be due to the complex nature of planning at the landscape level, as well as the data and model execution requirements (Collins et al. 2010).

Modeling fuel treatments using theoretical treatment design has progressed from regularly spaced, staggered treatment units, or SPLATS (Strategically Placed Area Treatments) (Finney 2001) to a spatially informed arrangement using optimization modeling (Finney 2004, 2006, 2007). The treatment-optimization model (TOM) (Finney 2004, 2006, 2007) identifies “ideal” treatment areas based on user-defined inputs in order to slow the rate and size of fire by placing treatments in flow paths across a landscape. These treatments can incorporate the realities of treatment constraints that land managers must recognize when planning fuel treatments (PACs, Spotted Owl Habitat, stream buffers, and accessibility). This incorporation of constraints allows for a greater representation of realistic arrangements across a landscape than the regularly spaced, staggered treatments associated with SPLATS (Finney 2001).

This study seeks to compare differing approaches to landscape fuel treatment by evaluating the predicted fire behavior and wildfire emissions among approaches. The Herger-Feinstein Quincy Library Group Pilot Project (HFQLG) (USDA 1999) sought to complete an arrangement of fuel treatments throughout the northern Sierra Nevada landscape based largely on the incorporation of local knowledge for informing placement of treatment areas (Moghaddas et al. 2010). Previous research for this same landscape demonstrated that this completed landscape fuel-treatment network was effective at reducing modeled fire behavior not only within treated areas, but across much of the landscape (Moghaddas et al. 2010; Collins et al. 2013). In this study, we add to this previous work by evaluating alternate fuel-treatment networks for the same landscape in order to quantify tradeoffs associated with different land-management constraints and objectives. Specifically, we examined conditional burn probabilities, fire area, and projected emissions for three different landscape-treatment scenarios and an untreated scenario.

Materials and Methods

Study Area

The Meadow Valley study area is located in Plumas National Forest in the northern Sierra Nevada at 39°56′N, 121°3′W (Fig. 1). The core study area boundary includes three Hydrologic Unit Code sixth-level watersheds, with modifications to the southern-most watershed based on the project area (USDA 2004a; Collins et al. 2013). This area has a Mediterranean climate with warm, dry summers and cool wet winters, with yearly mean precipitation of 1046 mm/year (Ansley and Battles 1998). The core study area is approximately 19,236 ha, with an elevation range from 850 to 2100 m (Fig. 1). The vegetation that comprises the Meadow Valley landscape primarily consists of mixed conifer forest (Schoenherr 1992; Barbour and Major 1995) with white fir, coast Douglas-fir (*Psuedotsuga menziesii* var. *menziesii*), sugar pine (*Pinus lambertiana*), Jeffrey pine (*Pinus jeffreyi*), incense-cedar, California black oak (*Quercus kelloggii*), and lesser amounts of other hardwood species. At higher elevations, red fir (*Abies magnifica*) can be found, interspersed with white fir. Western white pine (*Pinus monticola*) is found at higher elevations, lodgepole pine (*Pinus contorta)* in cold air pockets and riparian zones, western juniper (*Juniperus occidentalis*) on dry sites, California hazelnut (*Corylus cornuta*), dogwood (*Cornus spp.*) and willow (*Salix spp.*) in moist and riparian sites. Montane chaparral, as well as grasslands in meadows and dry sites, is mixed throughout the landscape. Tree density varies as a result of recent fire and timber management history, elevation, slope, aspect and soil composition. Historical fire return intervals, inferred from fire scars in tree rings, suggests a fire regime with predominantly frequent low-to-moderate intensity fires occurring at 7–19 years (Moody et al. 2006).

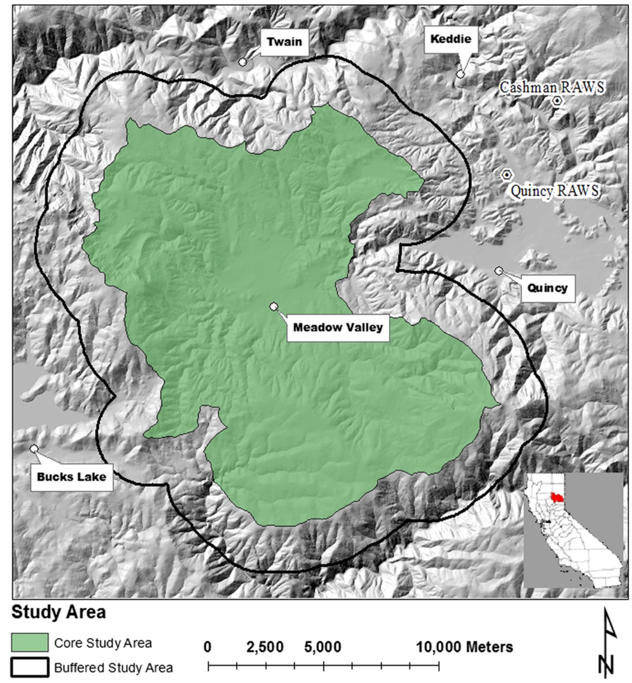


Fig. 1 Core and buffered study area boundaries for the Meadow Valley area, Plumas National Forest, California, USA. Weather data for fire modeling were obtained from both the Quincy and Cashman Remote Automated Weather Stations

The projects that contributed to the fuel-treatment network in Meadow Valley are a part of the larger HFQLG Pilot Project. The HFQLG project was directed by US Congress to implement a local community forest management vision that attempted to address a multitude of forest management objectives, including but not limited to, forest health, fire-severity reduction, wildlife habitat conservation, and stabilization of local economic conditions (Collins et al. 2013). The projects in Meadow Valley included a range of treatment types and intensities, as a product of changes in regional management direction (USDA 2001, 2004b) and land-management constraints across a diverse landscape (Collins et al. 2010; Moghaddas et al. 2010).

Plumas National Forest initiated fuel reduction projects in the Meadow Valley area in the late 1990s totaling approximately 9 % of the core study area. In 2005, the Meadow Valley Project was implemented, which linked the existing treatments with an additional 1650 ha of defensible fuel profile zone (DFPZs) and 231 ha of group selection (GS) in order to create a landscape-level fuel-reduction network. DFPZsare areas where fuel has been treated to reduce surface fuel loads, increase the canopy base height, and decrease canopy bulk density. DFPZsare essentially a fuelbreak, but limited to forested structure, and this term originated from the Quincy Library Pilot Project proposal for fragmenting fuels within the project area (Plumas, Lassen, Tahoe National Forests). Assessment of effectiveness of these treatment areas was completed following fire events associated within the overall project area. These results demonstrated the desired effect of modifying fire behavior, including rate of spread and intensity, in the majority of fire occurrences. The goal of DFPZsfor use as anchor points or defensible fire space during fire suppression efforts was also recognized in these treatment areas (Murphy et al. 2010). Within DFPZs, surface, ladder, and crown fuels were reduced. Conifers and hardwoods up to 51 cm DBH (Diameter at Breast Height) 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 (WUI), the upper DBH limit for harvest was 76 cm (USDA 2004a). Post-harvest treatments to reduce surface fuels included grapple piling, hand piling, pile burning and under-burning (Moghaddas et al. 2010).

The GS units included removal of all conifers up to 76 cm DBH, with individual units ranging from 0.25 to 1 ha in size. Site preparation following GS harvest consisted of mechanical grapple piling and burning. GS units were allowed to regenerate naturally or planted to a density of 270 trees/ha with a mix of sugar pine, ponderosa pine and Douglas-fir (USDA 2004a). Alternative treatments were also included within the fuel-treatment network. Mastication of shrubs and some small trees, with material left on site, as well as prescription burns in stands under moderate relative humidity and fuel moisture conditions also occurred (Collins et al. 2013). The complete Meadow Valley fuel-treatment network consisted of 3692 ha, or 19 % of the core study area (Table 3), and was implemented between 2003 and 2008 (Moghaddas et al. 2010; Collins et al. 2013).

Field Data Collection

Data were used from two distinct field sampling efforts. The first effort was aimed at a landscape-scale characterization using a stratified-random approach to establish plots, referred to hereafter as landscape plots. This approach used four strata: slope (3 levels: <15, 15–30, >30 %, elevation (3 levels: <1400, 1400–1600, and >1600 m), aspect (4 levels: N, E, S, and W), and dominant vegetation (explained below) (Collins et al. 2013) In total, there were 604 landscape plots, which were sampled between 2004 and 2006 (Moghaddas et al. 2010; Collins et al. 2013). The second field sampling effort was focused on treated areas, referred to as treatment plots. Plot locations were selected to capture the range in both treatment types and geographic locations of treatments throughout the study area and included 72 treatment plots. Pre-treatment sampling was conducted between 2002 and 2007, with post-treatment sampling between 2004 and 2009 (Moghaddas et al. 2010; Collins et al. 2013).

The two sampling efforts conducted and reported in previous research (Moghaddas et al. 2010; Collins et al. 2013), followed different plot sampling methodology based on the different objectives of the two efforts. Landscape plots were smaller and less intensive than the treatment plots to allow for a greater number of landscape plots that covered a much larger spatial extent. Landscape plots were circular with a fixed radius of 12.6 m, resulting in a plot area of 0.05 ha.

Treatment plots differed from landscape plots, and were rectangular: 50 m × 20 m, resulting in a plot area of 0.1 ha (Moghaddas et al. 2010; Collins et al. 2013). Variation in surface fuel loads in each treatment type was considered, however, this study sought to evaluate the placement of treatment opportunities on a landscape, not the inherent variability that surface fuels present in distinct treatment types. Therefore, surface fuel model designations described by Collins et al. (2013) for the Meadow Valley landscape were used to delineate the treated and untreated areas on a stand basis.

Data Integration

Tree data from both field measures were used to generate tree lists for pre- and post-treatment forested stands across the Meadow Valley landscape. Tree lists generated for the Forest Vegetation Simulator (FVS) contained the necessary input variables required for modeling within the ArcFuels platform (Ager et al. 2006; Ager et al. 2011). This included the associated stand identification number, tree count (based on an expansion factor from plot selection), tree diameter, species, height and crown ratio. The tree list component serves as a complete list of all tree records for each individual stands within the study area. Stand boundaries corresponded with mapped vegetation polygons (VESTRA 2003). Vegetation polygons were delineated using aerial photography and were assigned to California Wildlife Habitat Relationship vegetation classes. These classes capture broad differences in dominant species composition, and for tree-dominated classes, differentiate between dominant tree size classes (based on photo-interpreted crown radius) and density (based on photo-interpreted canopy cover). There were 1505 forested stands that were either within or intersected the core study area boundary, and ranged in size from 0.5 to 490 ha. The core study area was approximately 92 % forested stands, while grass and montane chaparral, and barren areas, such as lakes, made up the remaining 8 %. Tree lists that were generated from plot data were assigned to individual stands using an approach that matched the four strata used to determine landscape plots: slope, elevation, aspect, and dominant vegetation.

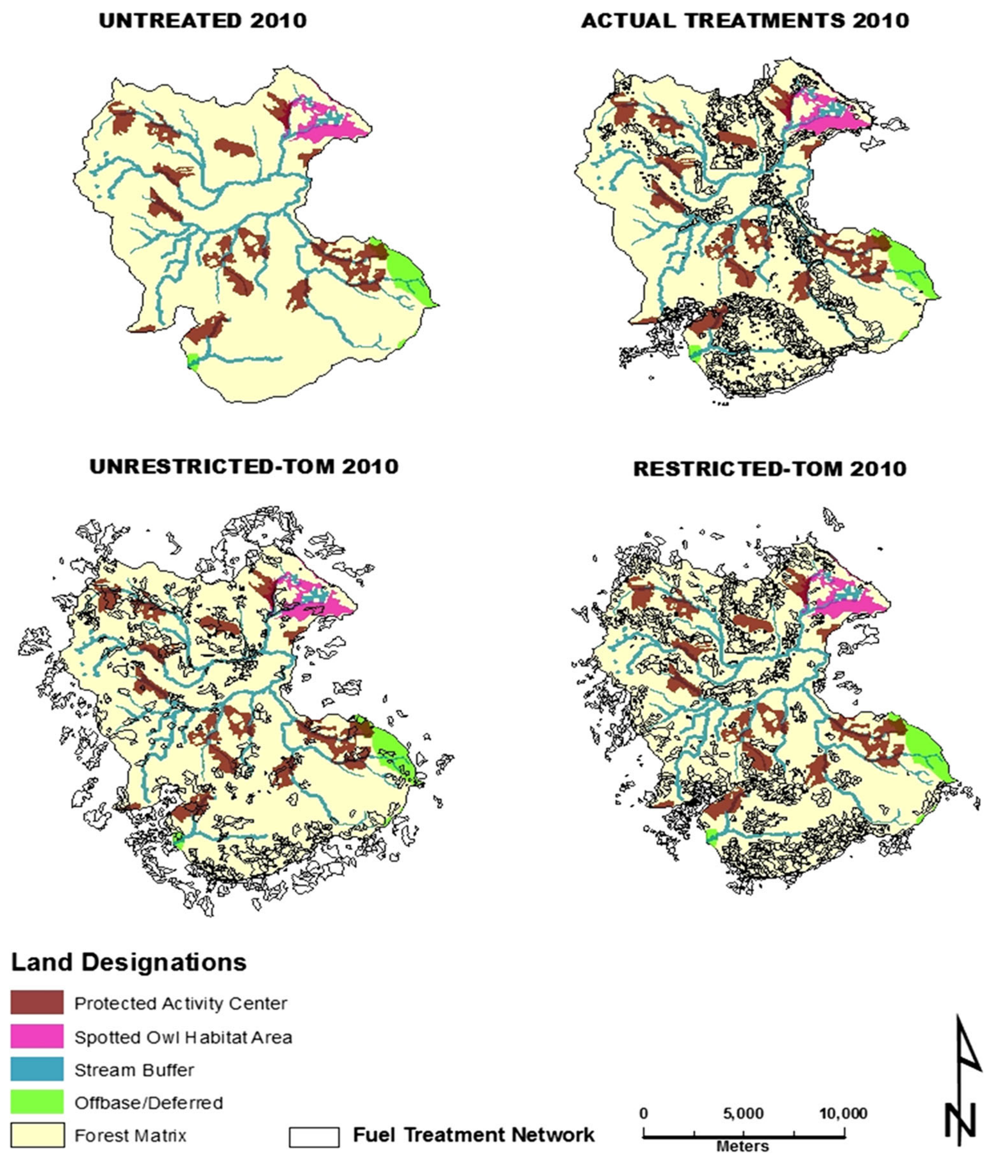
Stand polygons for the treatments completed by the HFQLG Pilot Project were compiled by the group's monitoring team (http://www.fs.fed.us/r5/hfqlg/monitoring/) and were overlaid on the stand vegetation layer provided by VESTRA (2003) following the integration from previous research (Moghaddas et al. 2010; Collins et al. 2013). The *actual* (Fig. 2) treated stands were assigned corresponding values from the treatment plots that matched the five treatment types described in Table 3. The same strata based approach used for assigning landscape plots was used in assigning treatment plots.

Polygons for theoretical treatments were derived from the *tom* (Finney 2007) module within the spatial fire behavior model FlamMap (Finney 2006) (Fig. 2). In order to execute *tom*, users need to create an "ideal landscape", which identifies the vegetation and fuel conditions for all areas where treatments are possible. For this study, two "ideal landscapes" were generated. The *unrestricted-tom* treatment scenario allowed treatment on all forested stands. The stands with barren or non-forest vegetation remained identified as untreatable. The *restricted-tom* treatment scenario sought to identify possible treatment stands within the study area based on major land allocations (Moghaddas et al. 2010). Stands were deemed not eligible for treatment if they fell within land allocations defined as PAC (spotted owl and northern goshawk), Spotted Owl Habitat Areas, Offbase and Deferred areas, and Stream buffers. Removing these land allocations from the treatment scenario is generally consistent with the current practices of the US Forest Service in the Sierra Nevada. Sampled vegetation and fuel conditions from the treatment plots that fell within DFPZs were used to define the conditions within all treatable stands in both the *unrestricted-* and *restricted-tom* treatment scenarios. This is in contrast to the *actual* treatments, which included five types of treatment (Table 3). DFPZs were used as the only treatment type in the modeled landscapes of this study in order to simulate a coordinated landscape-level-treatment network developed primarily for fire-hazard reduction.

TOM identifies optimal treatment areas by contrasting fire behavior predictions between an untreated landscape (pre-treatment) and the "ideal landscape" in order to disrupt fire spread. The model uses the minimum travel time algorithm (Finney 2002, 2006) to calculate major flow paths for fire spread, and assigns treatments to disrupt these flow paths (Finney 2007). The treatment areas identified by *tom* for both the theoretical treatment types (*unrestricted-* and *restricted-tom*) were limited to contiguous areas greater than 10 ha, as implementing smaller treatments identified by *tom*, which in some instances were as small as 0.25 ha, may be operationally infeasible.

Four databases were created with tree lists for all forested stands across the buffered study area. These databases represented four treatment scenarios: untreated (Pre-treatment), actual, unrestricted-tom and restricted-tom. The untreated database used tree lists from the pre-treatment sampling effort to populate stands within the treatment boundaries, and the strata method for populating the stands falling outside of the treatment boundaries. The actual treatment database was developed from the completed treatments, and the tree lists for treated stands used the post-treatment plot measurements of the same plots used in the pre-treatment database, while tree lists for stands outside of the treatment polygons used the plots assigned in the untreated database. The restricted- and unrestricted-tom treatment databases were assigned tree lists based on the theoretical treatment areas defined by the outputs from tom (Finney 2006; Finney 2007), and sought to apply the same approximate proportion of area treated as in the actual (19 %). Tree lists for the unrestricted- and restricted-tom landscapes were based on the post-treatment plot measurements that fell within the DFPZ treatment type. The four tree list databases were modeled using the FVS (Dixon 2002) to simulate forest structures, i.e., canopy base height (CBH), canopy height (CH), and canopy bulk density (CBD) using the integrated platform ArcFuels (Ager et al. 2006, 2011), which executes FVS and the fire and fuel extension (FFE) to generate the necessary stand structure inputs needed to calculate key fire behavior

Fig. 2 Core study area boundaries for the Meadow Valley area with stand treatment locations for four treatment scenarios. Actual treatments were implemented between 2003 and 2008, theoretical treatments are based on outputs from the treatment optimization model. Unrestricted-tom treatments overlap landscape-level constraints, whereas restricted-tom treatments are implemented around these constraints



parameters from runs of spatially explicit fire behavior models.

Fire Modeling

Weather information was obtained from the Quincy and Cashman Remote Automated Weather Stations (RAWS). 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 and direction recorded by the Quincy RAWS are well below those experienced in the study area (Moghaddas et al. 2010). The dataset used for weather inputs was chosen to mimic the weather simulation data used for the initial study of fuel-treatment effects (Moghaddas et al. 2010), and to replicate similar scenarios for the untreated and treated landscapes.

Weather conditions were limited to the dominant fire season for the Meadow Valley study area between June 1 and September 30 (Fig. 1), during the years 2002 and 2009. Models were calibrated with 90th percentile and above wind speeds, based on hourly observations, to generate multiple wind scenarios to be used during fire modeling. Dominant direction and average speed were identified from all observations at or above the 90th percentile value of 24 km/h. This resulted in three different dominant wind directions, each with its own wind speed and frequency of occurrence, based on the proportion of observations recorded at or above the 90th percentile value (Table 1).

Table 1 Weather parameters for fire simulations using RANDIG

Weather parameter	Value		
	Speed (km/h)	Direction (az.)	Relative frequency
Winds	31	225	0.77
	32	45	0.15
	31	180	0.08

Parameters were obtained from the Quincy and Cashman Remote Automated Weather Stations during the predominant fire season (June 1–September 30) for the years 2002 to 2009. Wind speeds and directions represent the dominant values from all 90th percentile and above observations

These modeled wind speeds were similar to those recorded during large spread events, specifically the 2012 Chips Fire, as well as the modeled wind speeds from previous research (Collins et al. 2013). The command line version of FlamMap (Finney 2006) is only capable of incorporating one "problem fire" within its weather input dataset. Long term data was evaluated from the available datasets of the Quincy and Cashman weather stations and were consistent with the associated weather conditions of the Chips Fire. Fuel moisture values were generated from 97th percentile (Table 2), as these conditions are associated with similar large fires that were difficult to control. Weather parameters obtained from the Chips fire by Fites et al. (2012), were greater than 97th percentile values during the modeled fire. As this was the most recent large fire spread occurrence in the area, using 97th percentile values and greater was considered representative of problem fires in the area.

Topographic inputs (slope, aspect, and elevation) were derived from a 10 m digital elevation model obtained from the National Elevation Dataset (http://ned.usgs.gov/). Stand structure and fuel layers were derived from FVS outputs using ArcFuels (Ager et al. 2006). For each stand, under each of four scenarios (untreated, actual, unrestricted-tom, restricted-tom), fuel model assignment was computed outside of FVS using the same criteria as Collins et al. (2013). Our study area included a 2 km buffer around the core study area. This buffered study area, used during fire modeling, was approximately 34,335 ha. The buffered study area was necessary in order to avoid edge effects during fire modeling, but output data for burn probability was only used from the core Meadow Valley study area (Table 3).

Table 2 Fuel moisture values for modeling simulations in FlamMap (Treatment Optimization Model) (Finney 2006) and RANDIG

Fuel type	Fuel moisture (%)
1 h	2
10 h	2
100 h	5
Live herbaceous	35
Live woody	60

Parameters were obtained from the Quincy and Cashman Remote Automated Weather Stations during the predominant fire season (June 1–September 30) for the years 2002 to 2009. Fuel moistures represent the 97th percentile and above observations

A command line version of FlamMap (Finney 2006), called RANDIG, was used to model fires across the buffered Meadow Valley landscape (Fig. 1). RANDIG uses the minimum travel time method (Finney 2002) to simulate fire spread based on user defined inputs for: number/pattern of ignitions, fire duration, dominant wind speed and direction, fuel moistures, topography, stand structure, and fuels. For each treatment scenario (untreated, actual, unrestricted-tom, restricted-tom) RANDIG simulated 10,000 random ignitions, each burning for a 240 min (4 h) burn period. This burn period duration was selected to match simulated fire sizes that approximated large spread events observed in recent wildfires in the Meadow Valley area (Moonlight 2007, Wheeler 2007, Rich 2008, Chips 2012) (Ager et al. 2010), as well as matching simulation times from previous research (Collins et al. 2013). The large number (10,000) of ignitions used during fire modeling was chosen due to the high deviation between individually simulated fires and their outputs when compared to the mean value of each of these outputs. The large number of ignitions allows for an assumption that these mean values are representative of a statistically significant mean value.

For each treatment scenario RANDIG outputs overall conditional burn probabilities, computed by dividing the total number of times a pixel burns by the total number of simulated fires (for this study simulated fires is 10,000), as well as marginal conditional burn probabilities for 20 flame length classes (0–10 m in 0.5 m increments). In order to isolate the more problematic-modeled fire (regarding fire effects and fire suppression), analysis was completed on burn probabilities where flame lengths were greater than 2 m. All marginal burn probabilities for flame length classes greater than 2 m were summed together for analysis and this threshold has been used to identify problematic fire in previous research (Collins et al. 2011; Ager et al. 2012; Collins et al. 2013). Burn probabilities were imported into ArcGIS software for data analysis. Mean conditional burn

Table 3 Summary of treated areas for three different treatment scenarios compared

Treatment model	Treatment category	Treated area within study area (ha)	Proportion of treated area	Proportion of total study area	Post-treatment surface fuel model[a]
Actual	Mechanically thinned and prescription-burned	1588	0.43	0.083	183
	Prescription-burned	1071	0.29	0.056	183
	Hand-thinned and pile burned	480	0.13	0.025	184
	Masticated	309	0.08	0.016	142
	Group selection harvested	240	0.07	0.012	201
	Total	**3688**	**1.00**	**0.192**	
Unrestricted-tom	Mechanically thinned and prescription-burned	3578	1.00	0.186	183
Restricted-tom	Mechanically thinned and prescription-burned	3770	1.00	0.196	183

See "Materials and Methods" section for explanation of each scenario

The unrestricted- and restricted-tom treatment scenarios use only Defensible Fuel Profile Zone (DFPZ) treatments in treatment areas across the same landscape

[a] Fuel Models were matched with data and results from Collins et al. (2013)

probabilities, from flame lengths greater than 2 m, as well as mean fire area, were calculated for each treatment scenario (untreated, actual, unrestricted-tom, restricted-tom). RANDIG also outputs 10,000 fire perimeters from each random ignition, and these were used for emissions modeling.

Emissions Modeling

Emission Estimation System 2 (EES2) is a wildland fire emission estimation system created for the California ARB in compliance with the State of California Global Warming Solutions Act of 2006 (AB 32). This project developed a fire modeling program which combined the use of the ArcGIS with the First Order Fire Effects Model (FOFEM) (Lutes et al. 2013), as well as the California Vegetation map in two separate representations (FCCS and SAF/SRM) (Clinton et al. 2006). EES2 estimates GHG (greenhouse gas) as well as particulate matter emissions using fire perimeters and FOFEM (Reinhardt 2003). This system was developed as the Emission Estimation System (Clinton et al. 2006) and was recently updated to include two different vegetation classifications derived from California fuel layers. This study incorporated the LANDFIRE Fuel Characteristic Classification System (Ottmar et al. 2007), which demonstrates higher accuracy for predicting GHG emissions in the northern Sierra Nevada (Lydersen et al. 2014). EES2 designates the landscape within each fire perimeter into "stands" of varying FCCS types, and batch runs these stands through the FOFEM 5.0 batch processing option (Reinhardt 2003). These stands are then processed into a spatial context by linking the per area emissions output for each FCCS type and the area of each "stand" within a fire perimeter. The total emissions output for each FCCS type within the fire perimeter can then be summed for fire perimeters outside of the EES2 program.

Outputs from RANDIG provided 10,000 "wildfire" perimeter polygons for evaluating mean emissions values for each treatment scenario. The pixel size resolution for EES2 can be as fine as 1 m; however, for consistency between all models, a 60 m resolution was used. This study used several fire dates (2002–2010) from local problematic fires (Rich Fire 2008, Silver Fire 2010, Storrie Fire 2000, Moonlight Fire 2007) for the monthly dates of fuel moistures. Outputs from EES2 included metric tons per hectare of PM 2.5 (Particulate matter), PM 10.0, NO_x and SO_2, as well as CO and CO_2. EES2 can output emission values for both flaming duration and smoldering duration, both of which were incorporated into analysis. All values for emissions were compiled outside of EES2 for each treatment scenario and 10,000 fire perimeters, with mean values of each emission type during smoldering and flaming combustion analyzed separately. In most cases, emissions during flaming combustion were much less than those during smoldering combustion, thus the values were combined as a total emissions value.

EES2 is not capable of capturing treatment modifications to stand structure or surface/ground fuel. As a result, all scenarios were run with the current cross-walked FCCS vegetation map, meaning stands which received treatments in the actual, unrestricted-tom, and restricted-tom treatment scenarios had the same vegetation type and fuel load as the untreated scenario. In order to quantify the possible reductions in emissions due to application of treatments, the calculated mean value of emissions for each treatment scenario was multiplied by mean fire area for the respective scenarios to obtain the total emissions for an "average" fire on the landscape.

Results

Fire Modeling

Conditional burn probabilities for problematic fire (>2 m flame lengths) within the core study area of Meadow Valley for the untreated landscape are noticeably greater than in the actual, unrestricted-tom, and restricted-tom treatment scenarios (Fig. 3). The central and eastern portions of the landscape had the highest burn probabilities in the untreated scenario. In all three treatment scenarios, burn probabilities across the landscape were noticeably reduced; however, they varied in the location of reduction (Fig. 3). The strongest reduction in the actual treatments, relative to the untreated one was in the central and eastern portions of the landscape; however, they were not as noticeable as the reductions in the central portion of the landscape for the unrestricted-tom and restricted-tom treatments (Fig. 3). The actual treatments also had higher burn probabilities in the north-east portion of the landscape than in the unrestricted-tom and restricted-tom treatment scenarios. Moderate conditional burn probabilities still occurred in the central portion of the unrestricted-tom treatment, but the south-eastern portion of the landscape showed the highest burn probabilities. Mean conditional burn probabilities for the three treatment scenarios within the core study area were approximately half that of the untreated scenario (Fig. 4). The unrestricted-tom treatment

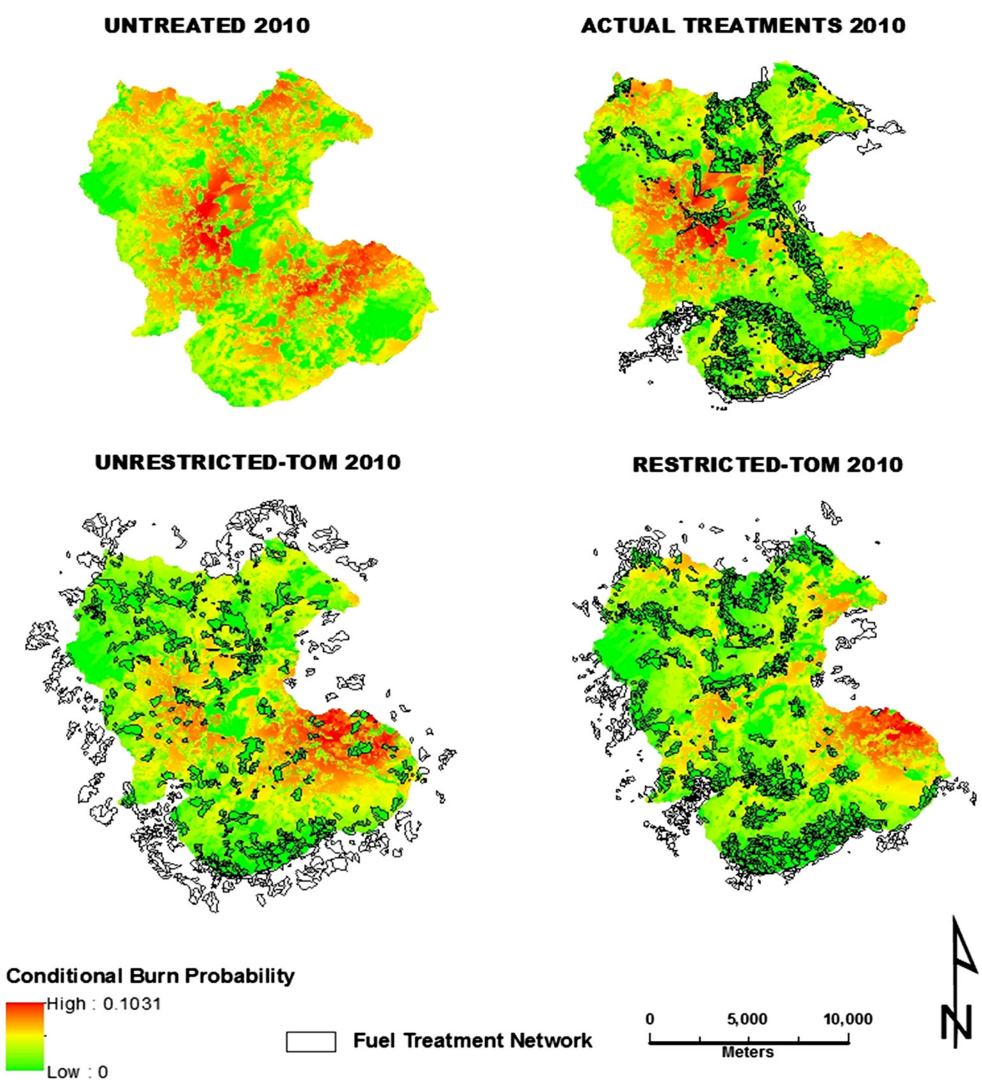


Fig. 3 Conditional burn probabilities across the Meadow Valley core area. Conditional burn probabilites are for simulated flame lengths greater than 2 m. Burn probabilities are based on 10,000 randomly placed ignitions simulated using RANDIG. Treated areas under the three treatment scenarios are displayed

had the highest mean conditional burn probability among the three treatment scenarios. While all treatment scenarios resulted in reductions in mean conditional burn probability when compared to the untreated scenario, the restricted-tom treatment had the greatest calculated reduction in burn probability across the core study area (Fig. 4).

Mean fire area in the untreated scenario was greater than that in any of the treatment scenarios (Fig. 5). The untreated scenario (2010) had a mean value of 1877 ha (240 min burn periods) (Figs. 4, 5). The unrestricted-tom treatment had a slightly higher mean value for fire area; however, it was less than that of the actual treatments by approximately 100 ha (Figs. 4, 5). The reduction in fire area was the greatest in the restricted-tom treatment, with a mean value of 1030 ha (Fig. 5), or nearly half that of the untreated scenario.

Emissions Modeling

Values for both PM 2.5 and PM 10 emission outputs during the combined flaming and smoldering combustion were higher in the untreated scenario, but differences between the actual, unrestricted-tom, and restricted-tom scenarios were negligible (Table 4). Values for both PM 2.5 and PM 10 were the lowest in the restricted-tom treatment scenario, at approximately half that of the untreated scenario. Total emissions of PM 2.5 and PM 10 in the unrestricted-tom treatment scenario was greater than the restricted-tom treatment, but was less than the actual treatment (Table 4).

Trends seen in particulate matter (PM) emissions were similar to those seen in carbon emissions. Greater values during combined types of combustion were produced in the untreated scenario than in the three alternate treatment scenarios, with the restricted-tom treatment showing greatest reduction. Values for CO_2 also showed significant decreases in the alternate treatment scenarios compared to the untreated scenario (Table 4). The restricted-tom treatment scenario had the greatest reduction in CO_2 emissions from the untreated scenario.

Values for NO_x followed similar trends as those seen in carbon and particulate matter emissions, with the greatest reduction being seen in the restricted-tom treatment scenario (Table 4). SO_2 also showed similar trends in reduction of emissions in the alternate treatment scenarios compared to the untreated scenario. The greatest reduction in SO_2 emissions is seen in the restricted-tom treatment, followed by the unrestricted-tom and actual treatments (Table 4).

Discussion

The reduction in conditional burn probability across a landscape with coordinated fuel treatments is not necessarily a new finding. It has been reported several times in the western US forests (Ager et al. 2007; Finney et al. 2007; Ager et al. 2010; Moghaddas et al. 2010; Collins et al. 2011, 2013) and has been studied in the Meadow Valley study area specifically by Moghaddas et al. (2010) and Collins et al. (2013). What is notable about the current study is the incorporation of theoretical modeling and analysis of different treatment scenarios across a landscape and the subsequent decreases in conditional burn probability (Figs. 3, 4), fire areas (Fig. 5), and emissions in all categories (CO, CO_2, NO_x, SO_2, PM 2.5, PM 10) (Table 4). While conditional burn probability was the lowest in the restricted-tom treatment scenario, in all the three treatment scenarios, they were approximately half that of the untreated scenario (Fig. 4); however, all three treatment

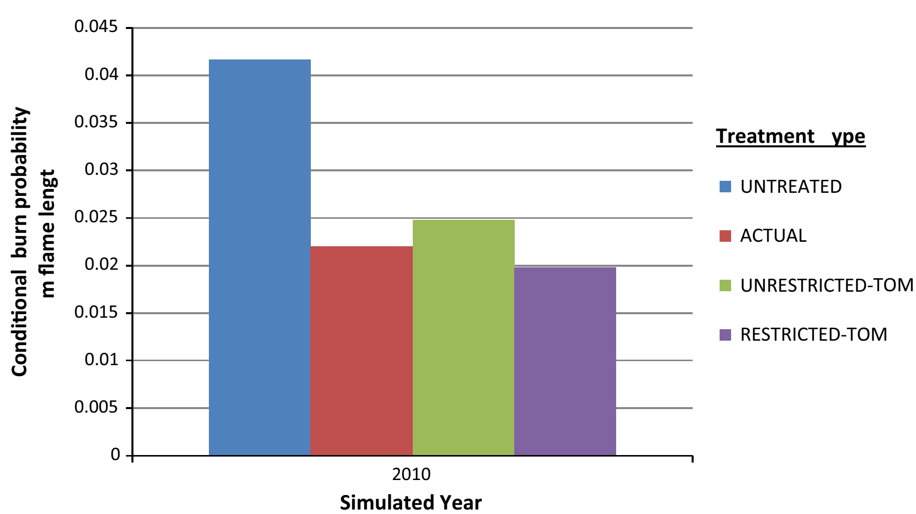


Fig. 4 Mean conditional burn probabilities for the simulated year 2010 and the four treatment scenarios across the Meadow Valley core area for which simulated flame lengths are greater than 2 m. Probabilities are based on 10,000 randomly placed ignitions simulated using RANDIG

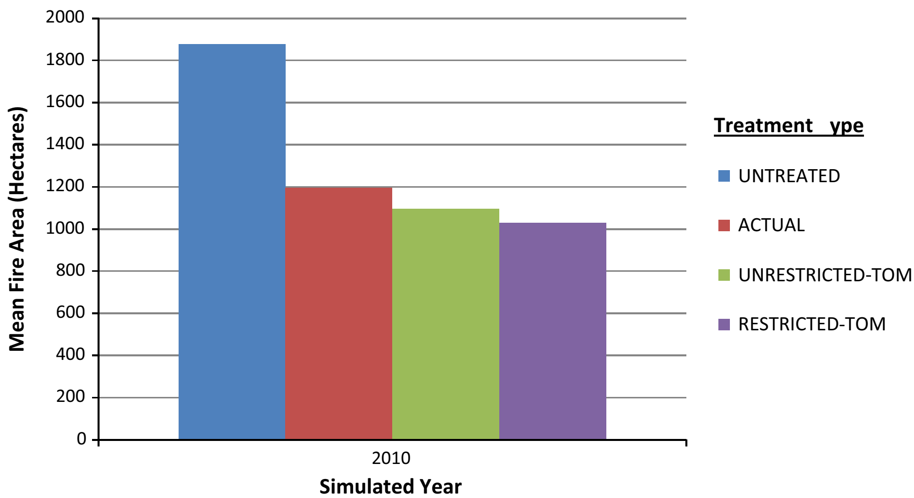


Fig. 5 Mean fire areas for a 4-h burn period for the four treatment scenarios across the Meadow Valley core area. Fire area is based on 10,000 randomly placed ignitions using RANDIG. The large number (10,000) of ignitions used during fire modeling was chosen due to the high deviation between individually simulated fires and their outputs compared to the mean value of each of these outputs. The large number of ignitions allows for an assumption that these mean values are representative of a statistically significant mean value

Table 4 Mean emissions outputs for PM 10, PM 2.5, CO, CO_2, NO_x, and SO_2 during fire activity for the four treatment scenarios across the Meadow Valley core area in megagrams (Mg)

Output type	Untreated	Treatment model		Restricted-tom
		Actual	Unrestricted-tom	
PM 10 (Mg)	2234.98	1456.54	1350.40	1276.61
PM 2.5 (Mg)	1894.16	1234.42	1144.47	1081.93
CO (Mg)	24,655.66	16,072.71	14,902.99	14,091.58
CO_2 (Mg)	136,539.45	88,719.97	82,169.41	77,508.46
NO_x (Mg)	66.07	42.54	39.28	36.79
SO_2 (Mg)	102.19	66.45	61.57	58.11

Emissions values are based on 10,000 fire perimeters generated from the randomly placed ignitions using RANDIG, which were input into the EES2 simulator. The large number (10,000) of ignitions used during fire modeling was chosen due to the high deviation between individually simulated fires and their outputs compared to the mean value of each of these outputs. The large number of ignitions allows for an assumption that these mean values are representative of a statistically significant mean value

scenarios still retained problem areas across the landscape, but in different locations (Fig. 4).

It is surprising to find similar reductions in conditional burn probability when comparing two theoretical model types, and a treatment scenario that was based on local knowledge and intuition (which is a similar result found in Collins et al. 2011, 2013), especially given that the theoretical models use an algorithm to define problem areas for major fire-flow paths (Finney 2006) and places of treatments within these paths in order to reduce burn probability. Despite the similarities in the decreased burn probabilities, it is remarkable that incorporating the restraints of PACs, California spotted owl habitat, northern goshawk habitat, and riparian areas, while planning for fuel treatments at the landscape level has a greater impact on the reductions in conditional burn probability, fire areas, and emissions than both the actual treatment scenarios, and more specifically, the unrestricted-tom treatment scenario.

The greater reductions of conditional burn probability, fire areas, and emissions may be due to the greater aggregation and continuity of fuel treatments (Fig. 2) seen in the restricted-tom treatment scenario compared to the unrestricted-tom scenario. Although percentage of landscape treated in the restricted-tom scenario was slightly higher (Table 3) than the unrestricted-tom scenario, the locations of treatments across the study area were less continuous in the latter. Differences in the continuity and aggregation of fuel treatments in the actual scenario compared to the restricted-tom scenario are also apparent. The actual treatment scenario has much greater aggregation and continuity than both of the theoretical treatment scenarios (Fig. 2), suggesting that an entirely continuous fuel-treatment network may not necessarily preclude greater reduction in burn probability and fire size.

Analysis of fire events that occurred between 1999 and 2009 throughout the Herger-Feinstein Quincy Library Group Pilot Project area (Plumas, Lassen, Tahoe National Forests) depicted two occurrences of fire behavior that overwhelmed fuel treatments (Murphy et al. 2010). The Dow Fire (1999), spotted over fuel-treatment areas, and the Moonlight Fire (2007), overwhelmed some fuel-treatments areas, while some were utilized for anchoring fire-suppression efforts. In all other reported cases, these treatment areas were effective at limiting the fire behavior and anchoring suppression efforts. This may imply that under certain conditions, fuel-treatment areas may not always be effective in meeting their goal and intent. It may be prudent in not only considering the continuity of fuel-treatment planning, but also the overall size of these areas in preventing fire spotting across fuel treatments, as well as treatment areas that cannot slow down the rapid, high-intensity fire behavior.

The restriction in the available treatment areas due to planning and operational constraints (Fig. 2) also seems to have little implication for reductions in conditional burn probability, fire areas, and emissions. Both the actual and restricted-tom treatments had land constraints (wildlife habitat, riparian buffers) that accounted for nearly 24 % of the Meadow Valley study area. This is in contrast to the unrestricted-tom treatments, which were only limited by stands that were non-forest type (8 %). When modeling these different approaches to planning across the landscape, all values (conditional burn probability, fire areas, emissions) were reduced in comparison to the untreated scenario. Despite the much greater area of constraints within the two restricted-type models, the results depict that there may be ways to plan across a restricted landscape that reduces hazardous fire potential with a higher proportion of non-treatable area. Finney et al. (2007) demonstrated that as the level of untreatable area reaches a value of 40 %, the optimization algorithm results are no different from the random placement of treatments. While this may apply here, results show that even with a greater than 20 % proportion of the landscape untreatable, conditional burn probability, fire areas, and emissions show reductions similar to or better than those of an unconstrained landscape. While this study did not incorporate a random placement of treatments scenario for comparison, it does suggest that incorporating constraints on the landscape at relatively modest levels (<25 %) may have similar desired effects as a treatment scenario that incorporates none.

The similarity in overall averages of burn probability, fire areas, and emissions outputs between all three treatment types, despite differences in treatment-type application, can be explained by the idea that the most effective method to change potential fire behavior is to alter the structure of forest fuels (Vaillant et al. 2009). Effective fuel treatments reduce flame length, fireline intensity, and the occurrence of crown fire. The use of mechanical or manual thinning of various intensities, mastication, whole tree removal, and prescribed fire tend to be the common fuel treatments used in the western mixed- and ponderosa pine forests. Although the actual treatments incorporated a variety of treatment types and scales compared to the unrestricted- and restricted-tom treatments (Table 3), which used DFPZs, this variety of treatment type likely is what contributed to the evenness in the reduction of conditional burn probability, fire areas, and emissions. Changing potential problematic fire behavior can be accomplished by reducing surface fuels, increasing CBH, and reducing CBD, in the order of their effectiveness. Using this approach breaks the continuity of not only horizontal surface and crown fuels, but also the vertical continuity of ladder fuels (Van Wagner 1977; Agee et al. 2000; Scott and Reinhardt 2001; Agee and Skinner 2005). Evidence that fuel treatments which change more than one characteristic of forest fuels, or employ more than one type of treatment, having greater effectiveness at reducing the risk of problem fire—has been demonstrated (Agee and Skinner 2005; Stephens and Moghaddas 2005; Schmidt et al. 2008; Stephens et al. 2009). The results of this study demonstrate that landscape-level treatments that incorporate a variety of fuel-treatment types using only local knowledge and intuition can be nearly as effective as modeling programs that incorporate only one type of treatment designed for reducing problematic fire potential.

The limits to the fuel characterization in EES2 program also prevented modeling a change in fuelbed types between the stands of the untreated landscape and the treated stands in each of the three treatment scenarios. It is likely that reductions in GHG and particulate emissions would be greater across all the three treated scenarios than those demonstrated in this study. Stephens et al. (2012b) demonstrated that at six sites in the western US, fuel-reduction treatments at the plot level decreased GHG emissions as well as particulate matter emissions compared to untreated plots. In California, GHG emissions, for both cap and trade, as well as federal law on reporting emissions, have become increasingly more important component of implementing fuel treatments, regeneration following fire, carbon sequestration, public health and aesthetic concerns, and is addressed by AB 32. Public health and aesthetic concerns largely drive the need for reporting particulate matter outputs from wildfire, as these outputs are considered to directly affect public health via inhalation, and may be considered to affect aesthetics as emissions from wildfire travel and settle into communities that otherwise may be unaffected by wildfire.

This study only captured differences in fire areas as a mode of calculation for decreases in landscape-level emissions, and thus the reductions in emissions in the treatment scenarios would likely show an even greater difference in comparison to the untreated scenario if the program allowed for change to the FCCS fuelbed type at the stand level. As it is becoming more prevalent for reporting GHG and particulate emissions, it is important to note that as new programs become available for assessing the landscape-level changes in forest and fuel structure, the availability of programs that more accurately account for changes across a landscape and alter wildfire emissions may also be necessary.

Management Implications

This study presents an analysis of treatment planning types at the landscape level that face many land managers with the constraints of PACs, California spotted owl habitat, northern goshawk habitat, and riparian areas. Although under current Forest Practice Rules (14 CCR Sects. 916.5, 936.5, 956.5 from Title 14, California Code of Regulations Chapters 4, 4.5 and 10) in California, the treatments of riparian areas in Class I, II, III, and IV streams are allowed with certain provisions. However, retaining this constraint was valuable for demonstrating that even with lack of treatment in riparian areas, as well as other restricted areas, reductions in hazardous fire potential, fire area, and emissions can be successfully achieved. There is research that presents fuel treatments as a potential detriment to ecosystem services, such as wildlife habitat (Lee and Irwin, 2005: Pilliod et al. 2006; Campbell et al. 2012), but these ecological effects following treatments (understory diversity, small mammals and song birds, erosion, and compaction) are short lived and relatively minor (Stephens et al. 2012b). The extent of overall forest change that follows fuel treatments is less than that of the change which follows severe wildfire without treatments (Stevens et al. 2014).

With the frequency of wildfires expected to increase, and the chance that stands burn multiple times increasing (Westerling et al. 2006), the protection of sensitive areas that are considered as constraints during the planning stages of fuel treatments is important to the retention of heterogeneous forests. Although mixed conifer Sierra Nevada forests may bear little resemblance to historical forest conditions (North et al. 2009b; Collins et al. 2014; Stephens et al. 2015), there are tools available for the planning and implementation of fuel treatments that reduce hazardous fire potential, as well as reduce the possible human effects associated with emissions. This study demonstrates that whether land managers use a similar intuitive model as was used in Meadow Valley, or a modeling tool such as FlamMap (Finney 2006) for planning fuel treatments, reduction in hazardous fire potential, fire area, and wildfire emissions can be achieved. The reality of constraints across the landscape may not reduce the effectiveness of treatments, assuming a level of constraint similar to or less than that for our study area ($\sim$25 %), but may in fact result in a more resilient forest. This attained ecological heterogeneity and resilient forest structure also reduces fire areas, severity patches, and emissions that are associated with carbon losses as per AB 32.

Acknowledgments The authors would like to thank all of those who helped in contributing to this research including Gary Roller, Bridget Tracy, Nick Delaney, Anu Kramer, Kurt Menning, Colin Dillingham, Klaus Scott, and Danny Fry. The authors also appreciate all of those who provided support in data collection and assistance in analysis and review, as well as the contributors to the Quincy Pilot Project from the Plumas National Forest.

References

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

Agee JK, Bahro BB, Finney MA, Omi PN, Sapsis DB, Skinner CN, van Wagtendonk JW, Weatherspoon CP (2000) The use of shaded fuel-breaks in landscape fire management. For Ecol Manag 127:55–66

Ager AA, Bahro B, Barber K (2006) Automating the fireshed assessment process with ArcGIS. Fuels management—how to measure success. U. S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Portland, pp 163–168

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

Ager AA, Vaillant NM, Finney MA (2010) A comparison of landscape fuel treatment strategies to mitigate wildland fire risk in the urban interface and preserve old forest structure. For Ecol Manag 259:1556–1570

Ager AA, Vaillant NM, Anderson J, Miller L (2011) ArcFuels user guide: for use with ArcGIS 9.X. Internal report. US Department of Agriculture, Forest Service, Pacific Northwest Research Station, Western Wildland Environmental Threat Assessment Center, Prineville, OR, USA. p 245

Ager AA, Vaillant NM, Owens DE, Brittain S, Hamann J (2012) Overview and example application of the Landscape Treatment Designer. General Technical Report PNW-GTR-859. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR, USA. p 11

Ansley JS, Battles JJ (1998) Forest composition, structure, and change in an old-growth mixed conifer forest in the northern Sierra Nevada. J Torrey Bot Soc 125:297–308

Auclair AND, Carter TB (1993) Forest wildfires as a recent source of CO_2 at northern latitudes. Can J For Res 23:1528–1536

Barbour MG, Major J (eds) (1995) Terrestrial vegetation of California: new expanded edition. California Native Plant Society, Davis

Campbell JL, Harmon ME, Mitchell SR (2012) Can fuel reduction treatments really increase forest carbon storage in the western US by reducing future fire emissions. Front Ecol Environ 10(2):83–90

Clinton NE, Gong P, Scott K (2006) Quantification of pollutants emitted from very large wildland fires in Southern California, USA. Atmos Environ 40(20):3686–3695

Collins BM, Stephens SL, Moghaddas JJ, Battles J (2010) Challenges and approaches in planning fuel treatments across fire-excluded forested landscapes. J For 108:24–31

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

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

Collins BM, Das AJ, Battles JJ, Fry DL, Krasnow KD, Stephens SL (2014) Beyond reducing fire hazard: fuel treatment impacts on overstory tree survival. Ecol Appl 24:1879–1886

Dixon GE (2002) Essential FVS: a user's guide to the forest vegetation simulator. Internal report. USDA, Forest Service, Rocky Mountain Research Station, Fort Collins, CO, USA. p 209

Dore S, Kolb TE, Montes-Helu M (2008) Long-term impact of a stand-replacing fire on ecosystem CO_2 exchange of a ponderosa pine forest. Glob Change Biol 14:1–20

Ferrell GT (1996) The influence of insect pests and pathogens on sierra forests. In: SNEP vol. II, 1996

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

Finney MA (2002) Fire growth using minimum travel time methods. Can J For Res 32:1420–1424

Finney MA (2004) Landscape fire simulation and fuel treatment optimization. In: Hayes JL, Ager AA, Barbour JR (eds) Methods for integrated modeling of landscape change. USDA Forest Service, Pacific Northwest Research Station, Portland, pp 117–131

Finney MA (2006) An overview of FlamMap modeling capabilities. Fuels management—how to measure success. U. S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Portland, pp 213–220

Finney MA (2007) A computational method for optimising fuel treatment locations. Int J Wildl Fire 16(6):702–711

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

Fites J, Ewell C, Bauer R (2012) The 2012 Chips Fire, California: a case study of fire behavior. http://www.fs.fed.us/adaptivemanagement/pub_reports/

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

Hurteau MD, Stoddard MT, Fule PZ (2011) The carbon costs of mitigating high severity wildfire in southwestern ponderosa pine. Glob Change Biol 17:1516–1521

Keyser TL, Zamoch SJ (2012) Thinning, age, and site quality influence on live tree carbon stocks in upland hardwood forest of the southern Appalachians. For Sci 58:407–418

Lee DC, Irwin LL (2005) Assessing risks to spotted owls from forest thinning in fire-adapted forests of the western United States. For Ecol Manag 211(1–2):191–209

Lutes DC, Keane RE, Reinhardt ED, Gangi L (2013) First order fire effects model. USDA Forest Service, Rocky Mountain Research Station, Missoula Fire Sciences Laboratory, Missoula

Lydersen JM, Collins BM, Ewell CM, Reiner AL, Fites JA, Dow CB, Gonzalez P, Saah DS, Battles JJ (2014) Using field data to assess model predictions of surface and ground fuel consumption by wildfire in coniferous forests of California. J Geophys Res 119:223–235

McKelvey KS, Johnston JD (1992) Historical perspectives on forests of the Sierra Nevada and the transverse ranges of southern California: forest conditions at the turn of the century. Chp. 11 in Verner et al. 1992

Meigs GW, Donato DC, Campbell JL, Law BE (2009) Forest fire impacts on carbon uptake, storage and emission: the role of burn severity in the Eastern Cascades, Oregon. Ecosystems 12:16–32

Miller JD, Safford HD, Crimmins M, Thode AE (2009) Quantitative evidence for increasing forest fire severity in the Sierra Nevada and Southern Cascade Mountains, California and Nevada, USA. Ecosystems 12:16–32

Moghaddas JJ, Collins BM, Menning K, Moghaddas EEY, Stephens SL (2010) Fuel treatment effects on modeled landscape level fire behavior in the northern Sierra Nevada. Can J For Res 40:1751–1765

Moody TJ, Fites-Kaufman J, Stephens SL (2006) Fire history and climate influences from forests in the northern Sierra Nevada, USA. Fire Ecol 2:115–141

Moritz MA, Parisien MA, Batllori E, Krawchuck MA, Van Dorn J, Ganz DJ, Hayhoe K (2012) Climate change and disruptions to global fire activity. Ecosphere 3(6):49

Murphy K, Duncan P, Dillingham C (2010) A summary of fuel treatment effectiveness in the Herger-Feinstein Quincy Library Group Pilot Project Area. United States Forest Service: R5-TP-031

North East State Foresters Association (2002) Carbon sequestration and its impacts on forest management in the Northeast. Concord http://www.nefainfo.org/publications/carbonsequestration.pdf

North M, Hurteau M, Innes J (2009a) Fire suppression and fuels treatment effects on mixed-conifer carbon stocks and emissions. Ecol Appl 19:1385–1396

North M, Stine P, O'Hara K, Zielinski W, Stephens SL (2009) An ecosystem management strategy for Sierran mixed conifer forests. USDA Forest Service, Pacific Southwest Research Station, General Technical Report. PSW-GTR-220

North MP, Collins BM, Stephens SL (2012) Using fire to increase the scale, benefits and future maintenance of fuels treatments. J For 110(7):392–401

Oliver CD, Larson BC (1996) Forest stand dynamics. John Wiley and Sons, New York **544 pp**

Ottmar RD, Sandberg DV, Riccardi CL, Prichard SJ (2007) An overview of the fuel characteristic classification system—quantifying, classifying, and creating fuelbeds for resource planning. Can J For Res 37(12):2383–2393

Perschel RT, Evans AM, Summers MJ (2007) Climate change, carbon, and the forests of the northeast. Forest Guild, Santa Fe

Pilliod DS, Bull EL, Hayes JL, Wales BC (2006) Wildlife and invertebrate response to fuel reduction treatments in dry coniferous forests of the western United States: a synthesis. USDA Forest Service, Rocky Mountain Research Station, Fort Collins, Colorado, General Technical Report. RMRS-GTR-173

Reinhardt E (2003) Using FOFEM 5.0 to estimate tree mortality, fuel consumption, smoke production and soil heating from wildland fire. Missoula, MT: USDA Forest Service, Missoula Fire Sciences Lab, p 7

Saspis D, Bahro B, Gabriel J, Jones R, Greenwood G (1996) An assessment of current risks, fuels, and potential fire behavior in the Sierra Nevada. In: SNEP vol. III, 1996

Schmidt DA, Taylor AH, Skinner CN (2008) The influence of fuels treatment and landscape arrangement on simulated fire behavior, Southern Cascade range, California. For Ecol Manag 255(8–9):3170–3184

Schoenherr AA (1992) A natural history of California. University of California Press, Berkeley

Scott JH, Reinhardt ED (2001) Assessing crown fire potential by linking models of surface and crown fire behavior. USDA Forest

Service, Rocky Mountain Research Station (Fort Collins, CO), Research Paper RMRS-RP-29

Spies TA, Hemstrom MA, Youngblood A, Hummel S (2006) Conserving old-growth forest diversity in disturbance-prone landscapes. Conserv Biol 20(2):351–362

Stephens SL, Moghaddas JJ (2005) Experimental fuel treatment impacts on forest structure, potential fire behavior, and predicted tree mortality in a California mixed conifer forest. For Ecol Manag 215:21–26

Stephens SL, Martin RE, Clinton NE (2007) Prehistoric fire area and emissions from California's forests, woodlands, shrublands, and grasslands. For Ecol Manag 251:205–216

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

Stephens SL, McIver JD, Boerner REJ, Fettig CJ, Fontaine JB, Hartsough BR, Kennedy P, Schwilk DW (2012a) Effects of forest fuel reduction treatments in the United States. Bioscience 62:549–560

Stephens SL, Boerner REJ, Moghaddas JJ, Moghaddas EEY, Collins BM, Dow CB, Edminster C, Fiedler CE, Fry DL, Hartsough BR, Keeley JE, Knapp EE, McIver JD, Skinner CN, Youngblood A (2012b) Fuel treatment impacts on estimated wildfire carbon loss from forests in Montana, Oregon, California, and Arizona. Ecosphere 3(5):38

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

Stephens SL, Bigelow SW, Burnett RD, Collins BM, Gallagher CV, Keane J, Kelt DA, North MP, Roberts LJ, Stine PA, Van Vuren DH (2014) California spotted owl, songbird, and small mammal responses to landscape fuel treatments. Bioscience 64:893–906

Stephens SL, Lydersen JM, Collins BM, Fry DL, Meyer MD (2015) Historical and current landscape-scale ponderosa pine and mixed-conifer forest structure in the Southern Sierra Nevada. Ecosphere 6(5): art 79

Stevens JT, Safford HD, Latimer AM (2014) Wildfire-contingent effects of fuel treatments can promote ecological resilience in seasonally dry conifer forests. Can J For Res 44:843–854

USDA (1999) Herger-Feinstein Quincy Library Group Forest Recover act Record of Decision. Record of Decision, Final Environmental Impact Statement. USFS. http://www.fs.fed.us/r5/hfqlg/archinves/record_of_decision/

USDA (2001) Sierra Nevada Forest Plan Amendment. USDA For. Serv. Final Supplemental Environmental Impact Statement

USDA (2004) Environmental assessment: Meadow valley defensible fuel profile zone and group selection project, p 113

USDA (2004) Sierra Nevada Forest Plan Amendment. USDA For. Serv. Final Supplemental Environmental Impact Statement R5-MB-046

Vaillant NM, Fites-Kaufman JA, Stephens SL (2009) Effectiveness of prescribed fire as a fuel treatment in Califonian coniferous forests. International Journal of Wildland Fire 18:165–175

Van de Water KM, Safford HD (2011) A summary of fire frequency estimates for California vegetation before Euro-American settlement. Fire Ecol 7(3):26–58

Van Wagner CE (1977) Conditions for the start and spread of crown fire. Can J For Res 7:23–34

Verner J, McKelvey KS, Noon BR, Gutierrez RJ, Could Jr., GI, Beck TW. 1992. The California spotted owl: a technical assessment of its current status. General Technical Report. PSW-GTR-133. U.S. Department of Agriculture, Pacific Southwest Research Station, Forest Service, Albany, p 285

VESTRA 2003. HFQLG vegetation mapping project final report. VESTRA Resources, Inc., Redding, p 19

Weatherspoon CP, Husari SJ, van Wagtendonk JW (1992) Fire and fuels management in relation to owl habitat in forests of the Sierra Nevada and southern California. Chp 12 in Verner et al. 1992

Westerling AL, Hidalgo HG, Craven DR, Swetnam TW (2006) Warming and earlier spring increase western U.S forest wildfire activity. Science 313:940–943