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Changes in fire behavior caused by fire exclusion and fuel build-up vary with topography in California montane forests, USA

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ABSTRACT

Wildfire sizes and proportions burned with high severity effects are increasing in seasonally dry forests, especially in the western USA. A critical need in efforts to restore or maintain these forest ecosystems is to determine where fuel build-up caused by fire exclusion reaches thresholds that compromise resilience to fire. Empirical studies identifying drivers of fire severity patterns in actual wildfires can be confounded by co-variation of vegetation and topography and the stochastic effects of weather and rarely consider long-term changes in fuel caused by fire exclusion.

To overcome these limitations, we used a spatially explicit fire model (FlamMap) to compare potential fire behavior by topographic position in Lassen Volcanic National Park (LAVO), California, a large (43,000 ha), mountainous, unlogged landscape with extensive historical and contemporary fuels data. Fuel loads were uniformly distributed and incrementally increased across the landscape, meaning variation in fire behavior within each simulation was due to topography and among simulations, to fuels. We analyzed changes in fire line intensity (FLI) and crown fire potential as surface and canopy fuels increased from historical to contemporary levels and with percentile and actual wildfire weather conditions.

Sensitivity to the influence of fuel build-up on fire behavior varied by topographic position. Steep slopes and ridges were most sensitive. At lower surface fuel loads, under pre-exclusion and contemporary canopy conditions, fire behavior was comparable and remained surface-type. As fuels increased, FLI and passive crown fire increased on steep slopes and ridgetops but remained largely unchanged on gentle slopes. Topographic variability in fire behavior was greatest with intermediate fuels. At higher surface fuel loads, under contemporary canopy fuels, passive crown fire dominated all topographic positions. With LAVO's current surface fuels, the area with potential for passive crown fire during actual fire weather increased from 6% pre-exclusion to 34% due to canopy fuel build-up. For topographically diverse landscapes, the results highlight where contemporary fire characteristics are most likely to deviate from historical patterns and may help managers prioritize locations for prescribed burning and managed wildfire to increase fire resilience in fuel rich landscapes.

1. Introduction

In recent decades, wildfire size and proportion of fires producing high severity effects have increased in western U.S. forests (Abatzoglou and Williams, 2016; Miller et al., 2009) with negative consequences for biodiversity, at-risk-species (Spies et al., 2006), and carbon sequestration (Hurteau et al., 2019), as well as damage to timber and property, and even loss of human lives (Calkin et al., 2014; Cohen, 2008). Fire sizes and proportion of high severity effects are growing due to a combination of our inability to suppress fires under increasingly frequent extreme fire weather conditions related to climate change (Collins, 2014; Westerling, 2016; Williams et al., 2019) and large contiguous areas with uncharacteristically high fuel loads (*e.g.* Covington and Moore, 1994; Fulé et al., 2009; O'Connor et al., 2014) resulting from a century of fire exclusion (Agee and Skinner, 2005; North et al., 2012). High intensity fires can cause a shift to non-forest over wide areas because of poor post-fire tree regeneration and increases in shrubs or grasses, particularly in drier forests that used to burn frequently (Coop

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et al., 2016; Davis et al., 2018). Avoiding long-term vegetation shifts by enhancing and maintaining ecosystem resilience (i.e., capacity to regain and retain defining characteristics after disturbance) has become a central concern in public land management (Hessburg et al., 2015, 2019).

Reconstructions of fire excluded western forests have quantified the extent to which fuel loads and forest structure deviate from their historical range of variability, (HRV) (Keane et al., 2008; Morgan, 2004; O'Connor et al., 2014). Modeling studies demonstrate how, in fuel-limited forest types, these deviations result in more extreme fire behavior than was historically experienced (Steel et al., 2015; Taylor et al., 2014). There is also compelling evidence from empirical and modeling studies that forests restored towards HRV conditions with fuel treatments are more resilient to fire in face of near-term (Flatley and Fulé, 2016; Keane et al., 2018; Lydersen et al., 2017) and longer-term climate changes (Knapp et al., 2021; Vernon et al., 2018). However, the extent of fuel reduction treatments remain insufficient in most landscapes to moderate wildfire effects (North et al., 2015; Syphard et al., 2011). This deficit highlights a need to identify thresholds of potential concern, (TPC) (Moritz et al., 2013), for management action (Barnett et al., 2016) to maintain ecologically based governance (Twidwell et al., 2019), particularly in national parks and wilderness where mechanical treatments are restricted and prescribed burnings and wildfire effects are the primary agents for vegetation and fuels management (National Park Service, 2006; North et al., 2012).

Focusing on how topographic variables (e.g. slope shape, aspect, slope position) influence patterns of forest structure and fuels is an emerging framework for expanding understanding of current deviation from a pre-fire exclusion HRV reference (Dillon et al., 2011; North et al., 2009; Skinner et al., 2018). The influence of topography on vegetation characteristics including site productivity, forest composition and structure, and fuel type indirectly shapes historical fire regime characteristics (Merschel et al., 2018; O'Connor et al., 2014; Rollins et al., 2002). Due to overlying vegetation and moisture patterns, elevation is often a strong predictor of severity (Agee, 1993; Kane et al., 2015; Sturtevant et al., 2009). Terrain can also directly influence fire behavior and subsequent fire effects (Albini, 1976). For example, increasing slope angle alone can increase fire intensity and severity of effects at sites with equivalent fuel loads (Knapp and Keeley, 2006; Safford et al., 2009). Consequently, fire severity in western forests generally increases with slope angle. However, fuel accumulation can override historical topographic effects on fire severity patterns (Hessburg et al., 2019). The fuel thresholds at which novel patterns may develop are largely unexplored.

Extreme weather and interactions of weather and topography can amplify fire behavior. For example, alignment of slope and wind direction can result in higher fire intensity on windward vs. leeward slopes with similar fuels (Prichard et al., 2020). Altering fuel structure, such as lowering quantities of surface fuel or creating an open vertically discontinuous forest canopy, can moderate the combine effects of extreme weather and topography on fire behavior and effects (Ritchie et al., 2007). For western conifer and other fire-prone forests such as Mediterranean conifer (Lecina-Diaz et al., 2014; Mitsopoulos et al., 2019) and Australian dry scherophyll woodland (Bradstock et al., 2010) where extreme weather is increasing fire size and severity, a greater understanding of the interplay of topography, fuel accumulation, and extreme weather is needed to identify how contemporary fire characteristics deviate from HRV and to prioritize locations for prescribed burning and desired wildfire effects to increase forest resilience to wildfires (Moreira et al., 2020).

In this study, we use landscape fire simulations to examine the influence of topography and fuel load on potential fire behavior. Analysis of severity patterns following actual wildfires would be confounded by correlations between terrain, vegetation, and fuels, and the stochastic effects of weather. Our modeling framework controls the confounding effects by distributing an incremental series of fuel conditions uniformly across the study site. This permits us to identify the fuel thresholds that alter fire behavior in different terrain units. Our specific research questions were:

1) How does fire behavior vary with topography as canopy and surface fuels increase?
2) Does the surface fuel threshold at which fire type shifts from surface to crown vary with topography?
3) How does extreme fire weather alter topographic patterns of fire behavior under contemporary and historical fuel conditions?

We anticipated that topography would more strongly drive fire behavior, specifically intensity and fire-type, with pre-fire exclusion fuel conditions compared to contemporary fuels, resulting in greater historical variation by landscape position. We hypothesized fuel accumulation would eventually overwhelm topographic effects on fire behavior by generating more intense and homogenous patterns of fire behavior. We also predicted that extreme fire weather, particularly actual weather conditions from recent wildfires, would accelerate the shift in fire behavior.

2. Study area

We selected Lassen Volcanic National Park (LAVO), California as an example landscape because LAVO is a large (43,000 ha), mountainous, unlogged area where fire-suppression has been the only large-scale human impact on vegetation and fuel conditions. Additionally, use of fire is the main tool for management of ecological conditions, and parkwide spatially explicit data on contemporary and historical fuels estimates are available.

LAVO (elevation 1609–3187 m) lies at the southern end of the Cascade Range, a volcanic plateau punctuated by high volcanic peaks (Fig. 1a–c). Forest dominants co-vary with elevation (Parker, 1991; Schoenherr, 2017; Taylor, 1990, 2000). The lower elevation forests are dominated by ponderosa pine (*Pinus ponderosa*) and Jeffery pine (*P. jeffreyi*), and mixed conifer forests of Jeffrey pine (*P. jeffreyi*) and white fir (*Abies concolor*) occur at higher elevation. Upper montane forests are composed of red fir (*A. magnifica* var. *magnifica*), white fir (*A. concolor*), and western white pine (*P. monticola*). Lodgepole pine (*P. contorta* spp. *murrayana*) occupies low lying flats and moist depressions where cold air pooling impedes regeneration of other montane forest species. High elevation forests are dominated by mountain hemlock (*Tsuga mertensiana*) and whitebark pine (*P.albicaulis*) (Taylor, 1995). LAVO is dominated by gentle to moderate slopes and the mean slope angle is 19.0% with little area (0.5%) having slopes >100%. The climate is Mediterranean, characterized by warm, dry summers and cold, wet winters. Average daily temperature ranges at Manzanita Lake, California (elevation 1780 m) are −6.6 °C–5.0 °C in January and 7.5 °C–26.1 °C in July (WRCC 2009). Mean annual precipitation is 1040 mm, but inter-annual variability is high. Most precipitation (>80%) falls as snow between November and April, and mean annual maximum snowpack depth from the Lower Lassen Peak Snow Course in April is 4.6 m (1.6min-8.4 max) (NOHRSC 2010).

3. Methods

3.1. Model framework

We used the wildfire simulation model FlamMap (Finney, 2006) to simulate potential fire behavior (hereafter, fire behavior) across LAVO. Gridded fuel and topographic layers and fixed weather conditions are used as model inputs to produce spatially explicit estimates of fire behavior. FlamMap is deterministic and does not simulate specific ignitions or fire growth. Each calculation is done independently across cells in a gridded landscape.

All simulations were run at a 30 m resolution. Topographic inputs were elevation, slope, and aspect and were derived from digital

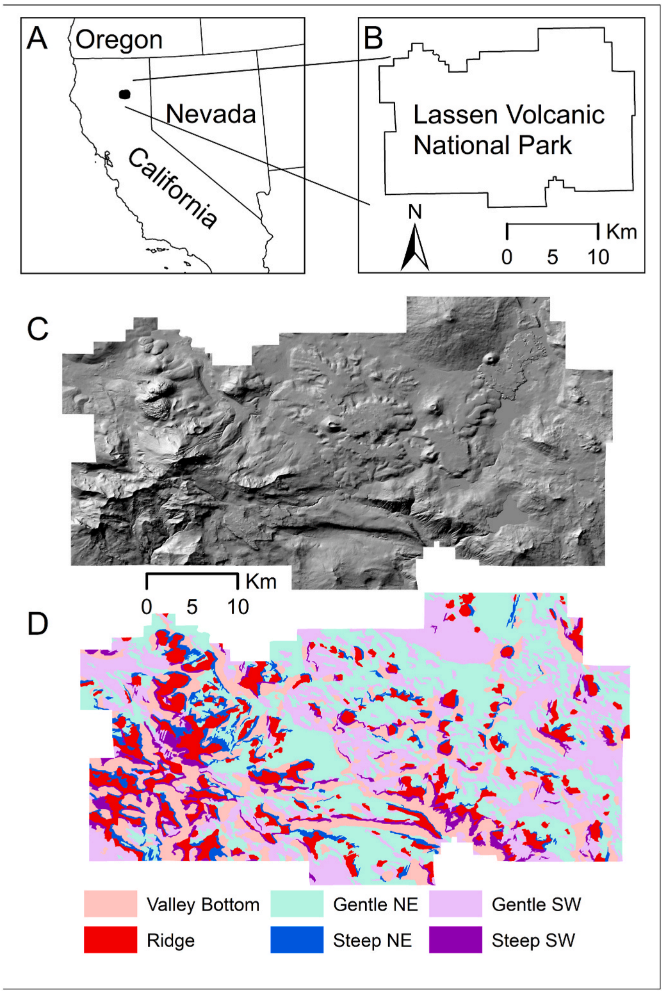

Fig. 1. Maps showing A. location of study area, Lassen Volcanic National Park within California, B. extent of the park. C.topographic features from DEM with hill shading D. Landscape Management Unit tool polygons designating topographic positions; ridges (red), valleys (pink), NE gentle slopes = light blue, NE steep slopes = blue, SW gentle = light purple, SW steep = purple, where, NE = 315°–135°, SW = 135°–315°, steep =>30%, gentle=<30%. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

elevation model (DEM) for LAVO (National Elevation Dataset (NED, https://apps.nationalmap.gov/). Fuel inputs included LAVO specific surface fuel models (Scott and Burgan, 2005) and canopy fuel parameters: canopy cover (CC), stand height, (HT), crown base height, (CBH), crown bulk density, (CBD) (Pierce et al., 2012). Fixed weather inputs were fuel moistures, wind speeds, and directions. The Finney (1998) crown fire calculation method was selected to estimate crown fire behavior.

To determine how fire behavior varies with topography as fuels increase, for each simulation we used only one surface fuel model and one set of canopy fuel parameters spread uniformly across LAVO (Fig. 2). We incrementally increased fuel loads to simulate fuel build-up. Gridded outputs were fire line intensity (FLI, $kW*m^{-1}$) and fire type (surface, passive crown, active crown). With uniform fuels, variation in FLI and fire type across LAVO within each scenario was attributable to variation in topography, while differences among scenarios at equivalent locations could be attributed to fuel changes. We examined the effects of weather by comparing results for equivalent fuels and topography with percentile versus actual fire weather parameters.

3.1.1. *Surface fuels*

Eight surface fuel models from Scott and Burgan (2005) were selected to represent the range of existing fuel conditions in LAVO based on LandFire and Park Service fuel maps in 2000. For each simulation, one of the following surface fuel models was distributed across LAVO: TL1—low load of compact short-needle litter, TL3—moderate load of conifer litter, TL4—moderate load of small downed limbs, TL5—high load of conifer litter, TL7—high load of conifer litter with some large diameter logs, TL8—moderate load of long-needle pine litter, TU1—timber understory with a low load of grass or shrubs, and TU5—timber understory of shrub or small tree understory with heavy forest litter (Scott and Burgan, 2005). These sequences of fuel models also represent increasing surface fuel loads with forest development as coarse woody debris accumulates with increasing time since fire such as are evident in repeat photographs over a fire-free century in LAVO in the top two panels of Fig. 3.

3.1.2. *Canopy fuels*

Two canopy fuel conditions were used: One representing pre-fire exclusion condition and, the other, a contemporary forest under a policy of fire suppression. Each scenario contained single values for CC (%), HT (m), CBH (m), and CBD ($kg*m^{-3}$). The values for pre-exclusion and contemporary canopy fuels were respectively; CC, 20 and 50%, HT, 40 and 25 m, CBH, 5 and 1.5 m, CBD, 0.05 and 0.1 $kg*m^{-3}$.

The contemporary canopy fuel scenario parameters were developed for LAVO by Pierce et al. (2012) from a random forest model using remote sensing and topographic data derived from a DEM and 223 field plots with HT and CBH measurements at the tree level and CBD and CC measurements derived from hemispherical photographs at the plot level. For the pre-exclusion canopy fuels, we used mean values of HT, CBH, and CBD from a pre-fire exclusion forest reconstruction developed using dendroecological techniques for forests in the Sierra Nevada with similar composition to those in LAVO by Taylor et al. (2014). Values reconstructed by Taylor et al. (2014) were comparable to reconstructed values for other western forests reported by Fulé et al. (2004), Brown et al. (2008), and Scholl and Taylor (2010). For pre-exclusion CC, we reduced values in Pierce et al. (2012) by half because pre-fire exclusion forests had lower basal areas and densities (Taylor et al., 2014), and increases in forest cover due to fire exclusion are well documented in LAVO (Taylor, 2000) (Fig. 3) and elsewhere in the southern Cascades (Skinner and Taylor, 2018), Klamath Mountains (Skinner et al., 2018; Taylor and Skinner, 2003), and the Sierra Nevada (Lydersen and Collins, 2018; Scholl and Taylor, 2010).

3.1.3. *Weather*

A total of 5 weather conditions were used - three percentile weather and two weather conditions from actual wildfires. The 80th, 90th, and 97th percentile weather parameters, (i.e., fuel moistures for 1,10-, and 100-h fuels, woody and herbaceous fuels, and wind speeds at 6.2 m) were computed with FireFamily Plus (Bradshaw and Tirmenstein, 2010) for the fire season (June 1 -October 31) using weather data (1962–2011) from the LAVO Manzanita Lake RAWS station, elevation 1780 m (FAM et al., 2011). Because conditions during actual wildfires increasingly differ from percentile conditions (Jain et al., 2017), we also used actual fuel moistures and wind speeds from the most extreme days during two wildfires in LAVO; the day with the highest windspeeds during the Huffer fire (2008), and the day with the highest Energy Release Component, (ERC), during the 2012 Reading Fire (See Supplemental Table S1). Fuel moistures were not pre-conditioned in the model because in California the long dry season removes expected moisture differences between shaded and less-shaded forests (Estes et al., 2012).

Wind direction affects rates of fire spread and fire intensity, especially during hot and dry periods. For each set of weather conditions, we applied 3 wind direction scenarios: 1) uphill; 2) constant direction of 247°, the most common daytime wind direction for Manzanita Lake during the fire season, and 3) variable speeds and directions based on WindNinja (Forthofer et al., 2009). WindNinja simulates the effect of terrain on wind speed and direction, and these gridded winds can

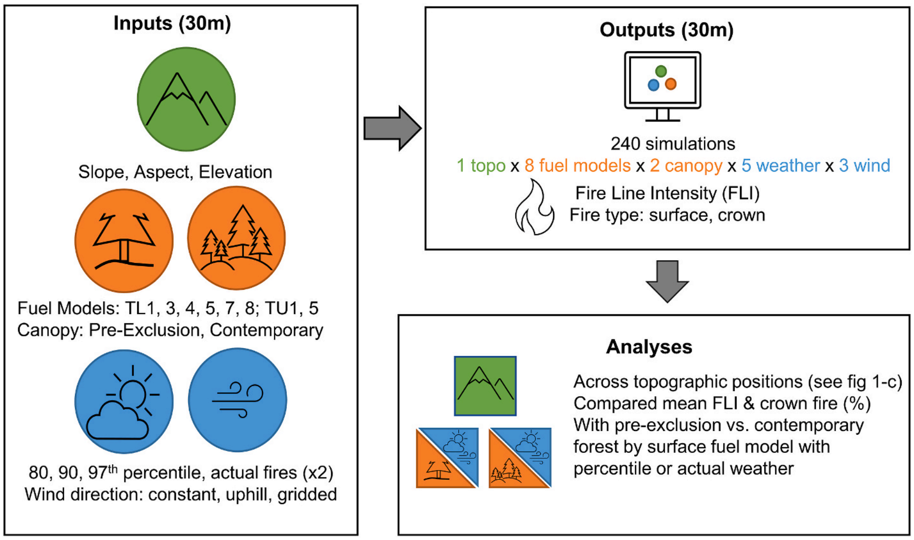

Fig. 2. Input, outputs and data analysis for modeling fire behavior with Flammap across Lassen Volcanic National Park, CA.

increase the accuracy of fire behavior predictions (Finney, 2006; Stratton, 2006).

3.2. Simulations

To determine how fire behavior varies with topography as fuels increase, we incrementally increased fuel loads to simulate fuel build-up. To compare the effects of percentile and more extreme recent actual fire weather conditions, for each combination of surface and canopy fuels, the model was run for the 5 weather scenarios (3 percentile and 2 actual wildfire) each with 3 wind scenarios (constant, uphill, directional), for a total of 9 (3 × 3) percentile and 6 (2 × 3) actual weather scenarios, for 15 simulations per time period or 30 simulations per surface model, for a total of 240 simulations (Fig. 2).

3.3. Topographic units

To analyze fire behavior by topographic characteristics, we classified the landscape into six topographic positions defined by slope-aspect and position using the Landscape Management Units (LMUv2) tool (Underwood et al., 2010) and the 30 m DEM for the park. The landscape was divided into ridges, steep (>30%) northeast (315°–134°) and southwest (135°–314°) slopes, gentle (<30%) northeast and southwest slopes, and valley bottoms (Fig. 1d). We used this classification tool because the categories were devised for management planning based on ecologically meaningful characteristics (Underwood et al., 2010).

The LMU tool categorized LAVO as mainly gentle (<30%) slopes comprising *ca.* 43% of the study site (Table 1, Fig. 1d). Ridges covered 16% and valley bottoms 14%, respectively. The remaining area (26%) was steep (>30%) slope units. The mean slope of the NE and SW gentle units was 13% (SD ± 9.2). The mean slope of the SW steep units was 46% (SD ± 17.2) and the NE mean was 43% (SD ± 15.9).

3.4. Analysis

To identify how an increase in fuels and extreme weather alters fire behavior across the landscape, we report the percent change in mean FLI between pre-exclusion fuels and contemporary canopy fuels for each surface fuel model at 6 topographic positions with percentile and actual weather (Fig. 2). We also report the mean proportion of crown type fire as fuels increase.

To simulate concurrent increase in surface and canopy fuels due to fire exclusion, we selected a low surface load (TL1), moderate surface load (TL8), and high surface load (TU5) scenario and calculated the mean increase in FLI by topographic position for three changes: (i) from low-load pre-exclusion to a moderate-load contemporary; (ii) moderate-load pre-exclusion to high-load contemporary; (iii) from low-load pre-exclusion to high-load contemporary. In terms of fire suppression, in western US forests, FLI's > 346 kW^*m^{-1} are too intense for holding fire with a handline and require heavy equipment, while for values > 1730 kW^*m^{-1} torching and crowning are expected and control is anticipated to be extremely challenging (Alexander and Cruz, 2019).

4. Results

4.1. Canopy fuels and FLI

Differences in fire behavior between pre-fire exclusion and contemporary canopy fuel loads with equivalent surface fuel varied by topographic position (Table 2). With the lightest 3 surface fuel loads, mean FLI decreased from pre-fire exclusion to contemporary conditions across all topographic units with the greatest decreases on gentle slopes. In contrast, as surface fuels increased to the five higher surface fuel load models (TL5, TL7, TL8, TU1, and TU5), FLI increased, with the greatest increases on ridges (22–76%) and steep slopes (5–31%). Under three loads, TL5, TL8, and TU5, FLI also increased slightly (1–5%) on valley bottoms.

4.2. Surface fuels and fire type

The surface fuel load threshold for a change in fire-type from surface to passive crown fire following an increase in canopy fuel load also varied by topographic position. Under the pre-fire exclusion canopy fuel scenario, surface fire accounted for >99% of the modeled fire behavior across the landscape, except at the high load surface fuel model TU5 (Fig. 4). With TU5, 2–7% of steep slopes and ridges experienced passive crown fire (see also Supplementary Table S2). Under contemporary canopy conditions, with the 2 lightest surface fuel models (TL1, TL3), surface fire dominated (>99%) modeled fire behavior (Fig. 4). With increasing surface fuel loads, ridgetops, steep slopes, and valley bottoms had increasing proportions of passive crown fire, with ridgetops and steep south-facing slopes showing the greatest increases. At TL4, passive crown fire occurred on only ridges and steep slopes (1–2%). At increased loads, passive crown fire appeared on gentle southern slopes and increased on steep slopes and ridges. Passive crown fire was predominant across all topographic positions with high load TL8 under actual

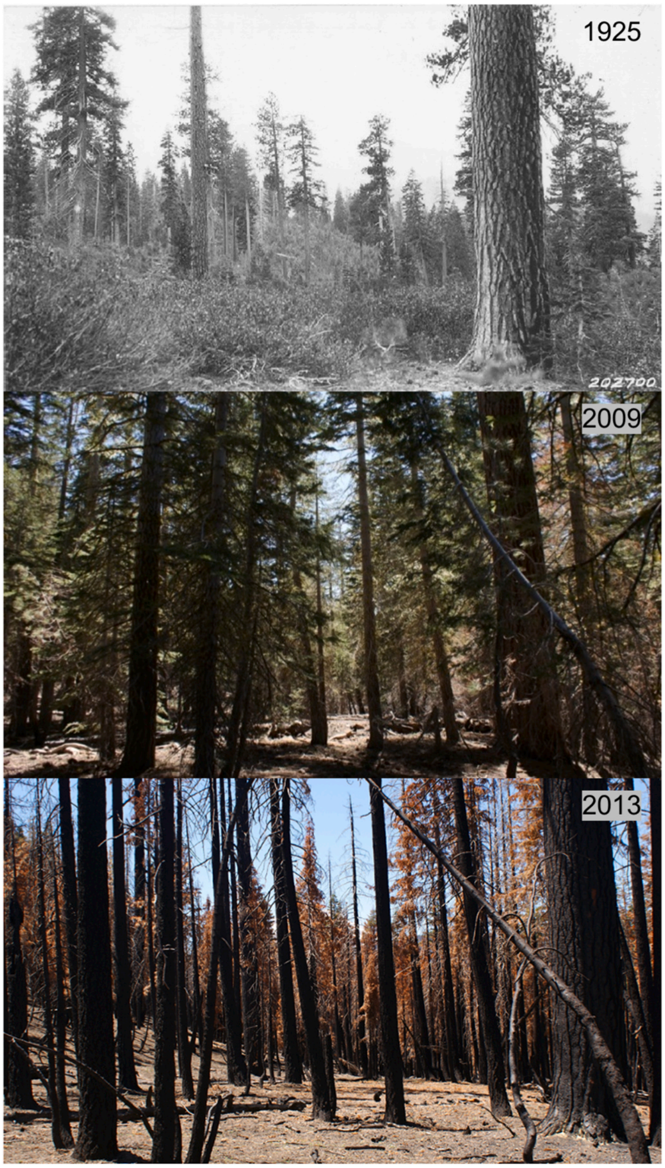

Fig. 3. Repeat photographs of a low-elevation mixed conifer forest in Lassen Volcanic National Park, CA illustrating build-up in canopy and surface fuels following a century of fire exclusion and effects of a subsequent wildfire. 1925-pre-fire exclusion, 2009 contemporary forest, 2013 after a 2012 wildfire, the Reading Fire.

Table 1
Area and proportion of Lassen Volcanic National Park, CA by topographic position unit (combination of slope position and aspect) defined by the Land Management Unit tool (Underwood et al., 2010) with the mean slope (%) and standard deviation by unit. Steep >30%, Gentle <30%.

Topographic Unit	Area (Ha)	Proportion (%)	Mean Slope%	Std Dev
Ridge	5542	13	36	23.4
SW Steep	2309	5	46	17.2
NE Steep	2242	5	43	15.9
SW Gentle	11,577	27	13	9.2
NE Gentle	14,584	34	13	9.2
Valley Bottoms	7263	17	25	19.0
Total	43,517	100%		

wildfire weather conditions. At the highest fuel (TU5), passive crown fire accounted for >99% of the fire behavior across all topographic positions under all weather conditions while active crown was predicted to occur in 1% of ridgetops.

4.3. *Fuel accumulation and FLI*

Simultaneous increases in canopy and surface fuel loads to simulate fire exclusion showed an increase in FLI modulated by topographic position (Table 3). FLI change was greatest on steep southern slopes (209–2095 kW*m^{-1}) followed by ridgetops (294–1862 kW*m^{-1}) and smallest on gentle slopes, especially gentle northeast slopes (83–844 kW*m^{-1}). An increase from low to moderate loads, on steep southern slopes and ridges a fire previously suppressible with a hand crew would shift to heavy equipment at a minimum. With the greatest increase in surface fuel load (TL1 to TU5) the increase in FLI during actual fire weather conditions for ridges and steep southern slopes (1862–2095 kW*m^{-1}) exceeds the suppression value 1730 kW*m^{-1} likely rendering fire suppression ineffective across these locations (Alexander and Cruz, 2019).

4.4. *Fire weather and FLI*

Compared to the percentile weather conditions, the higher wind-speeds and drier fuels recorded during actual wildfire weather conditions resulted in slight to modest increases in % FLI change and more crown fire. For the fuel accumulation scenarios, FLI increases with actual weather were 26%–72% greater than with percentile weather conditions (Table 3). The largest percentage increases occurred on gentle slopes. The proportion of potential passive crown fire on gentle slopes almost doubled with actual wildfire weather for TL5 and TL7, from 9% to 15% and from 7% to 15% respectively (Fig. 4, Supplemental Table S2). At high (TU5) and low (TU1) surface fuel loads, the proportions of passive crown fire remained similar for percentile and wildfire weather conditions.

4.5. *Fire behavior changes in LAVO*

About 65% of LAVO was forested in the year 2000. With actual surface fuel loads and actual fire weather for the park, when the canopy fuel loads were increased from pre-fire exclusion to contemporary levels, the proportion of passive crown increased (Table 4, Fig. 5a and b). With pre-fire exclusion canopy fuels, passive crown fire was predicted to occur in 6% of the forested landscape, including ridgetops, steep northern slopes, and valley bottoms (Table 4). With the contemporary canopy fuels, all topographic positions and 34% of the forest had potential passive crown fire, including around one-quarter of gentle slopes with more widespread crown fire on steep slopes and on all ridgetops (Fig. 5c, Table 4). Increased canopy fuels are predicted to lower FLI for the gentle slopes that comprise the majority (62%) of LAVO forest (Fig. 5d). In contrast, the remaining steeper slopes, ridges, and valley bottoms with moderate to high surface fuels models, are predicted to have an increase in FLI (mean 19%, range 1–74%) with contemporary canopy fuels.

5. Discussion

5.1. *Topography and fuel changes*

Landscapes that experience mixed severity fire effects such as the forests in LAVO represent high priorities for restoration because they are prone to exceed HRV in time since fire (Hessburg et al., 2005). However, the historical fire effects are difficult to quantify and define because they were driven by an interplay of multiple factors, most importantly fuel loads, weather, and topography (Steel et al., 2015). Our evaluation of fire behavior by modeling homogenous fuel loads across a mountainous

Table 2
Mean percent change (±95% CI) fire-line intensity by topographic position unit between the pre-exclusion and the contemporary time period canopy fuel scenarios for percentile 80,90, and 99, (Percent) and actual Huffer and Reading fire weather (Actual) conditions with each surface fuel model in Lassen Volcanic National Park, CA. *Slopes: Steep >30%, Gentle <30%.

Topographic Unit	Ridge		NE Steep* Slope		SW Steep* Slope		NE Gentle* Slope		SW Gentle* Slope		Valley Bottom	
Weather	Percent	Actual	Percent	Actual	Percent	Actual	Percent	Actual	Percent	Actual	Percent	Actual
Fuel Model	Mean Percent Change											
TL1	−12 ± 1	−14 ± 0.4	-7 ± 1	−11 ± 1	−12 ± 1	−12 ± 0.4	−21 ± 0.1	−23 ± 0.1	−21 ± 0.1	−22 ± 0.1	−15 ± 0.4	−18 ± 0.3
TL3	−11 ± 1	−14 ± 1	−21 ± 1	−12 ± 1	−8 ±1	−13 ± 1	−15 ± 0.1	−24 ± 0.1	−19 ± 0.1	−23 ± 0.1	−12 ± 1	−18 ± 0.3
TL4	1 ± 2	−3 ±2	−1 ±1	−9 ±2	−5 ±1	−9 ±2	−18 ± 0.1	−25 ± 0.1	−18 ± 0.1	−24 ± 0.1	−11 ± 1	−17 ± 1
TL5	74 ± 10	76 ± 11	24 ± 8	12 ± 8	30 ± 8	42 ± 10	−18 ± 0.1	−27± 0.1	−18 ± 0.1	−23 ± 0.1	5 ± 4	0 ± 4
TL7	19 ± 3	31 ± 5	5 ± 3	11 ± 4	5 ± 3	12 ± 4	−17 ± 0.1	−20 ± 0.1	−16 ± 0.1	−21 ± 0.1	−6 ±1	−6 ±2
TL8	53 ± 7	67 ± 8	24 ± 5	29 ± 5	31 ± 5	45 ± 6	−21 ± 0.1	−16 ± 0.1	−19 ± 0.1	−14 ± 0.1	5 ± 2	9 ± 2
TU1	40 ± 8	56 ± 10	17 ± 6	14 ± 8	10 ± 5	8 ± 7	−15 ± 0.1	−25 ± 0.1	−15 ± 0.1	−26 ± 0.1	0 ± 3	−11 ± 3
TU5	22 ± 3	29 ± 3	14 ± 2	4 ± 6	15\ ±2	6 ± 8	−13 ± 0.1	−29 ± 0.1	−12 ± 0.1	−27 ± 0.1	1 ± 1	−13 ± 2

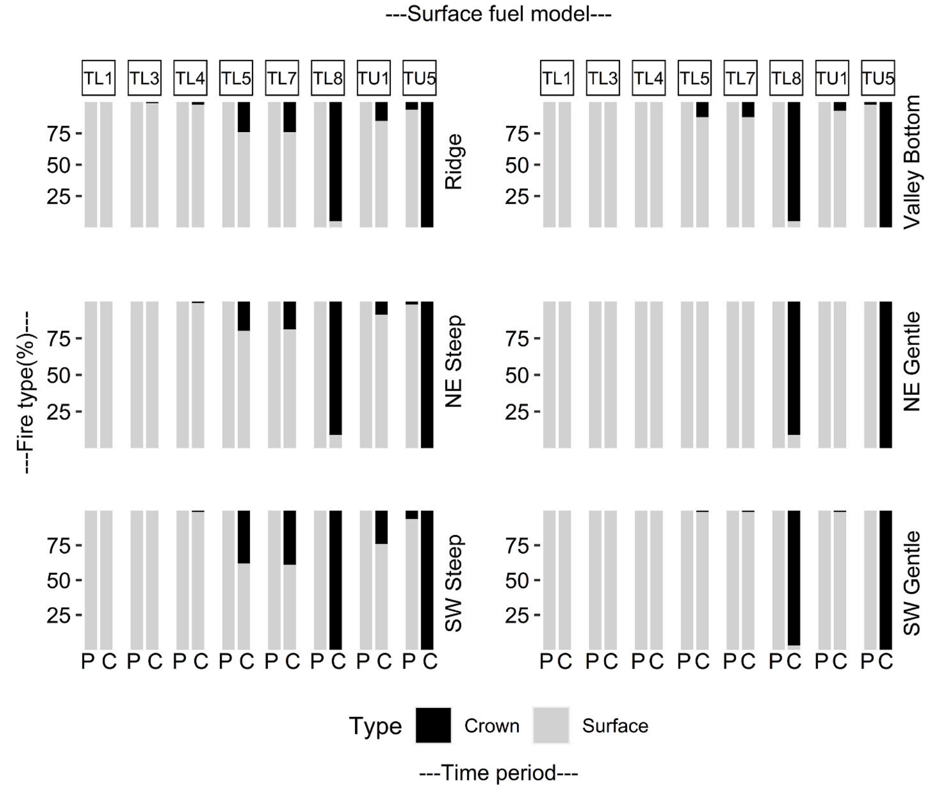

Fig. 4. Proportion of surface (gray) and passive crown (black) fire predicted under actual fire weather conditions by topographic position for pre-fire exclusion canopy (P) and, contemporary canopy (C) with 8 surface fuel models in Lassen Volcanic National Park, CA. Gentle = slopes <30%, Steep = slopes >30%, NE = 315°–135°, SW = 135°–315° *Fuel model TU5 current canopy fuel scenario has 1% active crown fire on ridges.

landscape demonstrates that topography is most influential on fire behavior when fuel loads are intermediate and least influential when fuel loads are high or low. At intermediate fuel loads, topographic position can both amplify and dampen the effects of fuel accumulation on fire behavior. Specifically, ridgetop and steep slopes have a lower threshold for fuel accumulation than other topographic positions and show the greatest percent increases in fire intensity and crown type fire when fuels increase. In contrast, gentle slopes and valleys require greater fuel build-up and more severe weather to undergo increases in crown fire. At high surface fuel loads, high severity fire becomes widespread and can occur on all topographic positions. Alternatively, low fuel loads may continue to burn with moderate fire behavior even during extreme weather.

In LAVO, the SW steep slopes show slightly greater FLI and crown fire proportion than for NE steep slopes. This is likely because the mean slope was higher for SW slopes (46% vs 43%), and because, for the constant wind direction scenario, the predominant wind direction during the fire season is a WSW wind that aligns with the SW facing slopes.

Table 3

Change in mean fire-line intensity, FLI, (kW*m^{-1}) by topographic position unit resulting from a shift from pre-exclusion to current canopy fuels and the indicated change in surface fuel load where low = fuel model TL1, moderate = fuel model TL8, high = fuel model TU5 under percentile (80,90, and 99%), and actual Huffer and Reading fire weather conditions in Lassen Volcanic National Park, CA. Steep >30%, Gentle <30% Slope, Bot = Bottoms.

Surface Fuel Load Change		Mean Change in FLI (kW*m^{-1}) (SE)	
	Topo, Unit	Percentile Weather	Actual Weather
Low to Moderate	Ridge	294 (8.1)	370 (10.0)
	NE Steep	223 (5.0)	289 (6.2)
	SW Steep	291 (6.9)	383 (9.8)
	NE Gentle	83 (0.1)	128 (0.1)
	SW Gentle	88 (0.1)	141 (0.1)
	Valley	152 (1.9)	203 (2.6)
Moderate to High	Ridge	1105 (16.3)	1593 (22.4)
	NE Steep	914 (11.6)	1191 (16.3)
	SW Steep	1203 (15.8)	1781 (23.9)
	NE Gentle	437 (0.2)	664 (0.3)
	SW Gentle	468 (0.3)	726 (0.3)
	Valley Bot	691 (4.5)	1009 (6.7)
Low to High	Ridge	1189 (16.3)	1862 (23.9)
	NE Steep	971 (11.3)	1424 (16.9)
	SW Steep	1338 (15.6)	2095 (25.0)
	NE Gentle	491 (0.2)	844 (0.3)
	SW Gentle	538 (0.3)	916 (0.4)
	Valley Bot	770 (4.5)	1231 (6.9)

Table 4

Forested topographic units in Lassen Volcanic National Park, CA with proportion of pre-exclusion (Pre) and contemporary (Cont) forest with potential passive crown fire and mean (range) % crown fire with the year 2000 surface fuel loads. Steep >30%, Gentle <30% Slope, Bot = Bottoms.

Topo. Position	Proportion of forest %	Proportion w/crown fire potential (%)		Mean (range) crown fire potential (%)	
		Pre	Cont	Pre	Cont
Ridge	11	20	100	6 (6–6)	24 (1–99)
NE Steep	5	17	33	2 (2–2)	62 (1–100)
SW Steep	5	0	43	0	80 (1–100)
NE Gentle	35	0	19	0	97 (91–100)
SW Gentle	28	0	26	0	87 (1–100)
Valley Bot	16	19	32	2 (2–2)	78 (5–100)
	Forest total	**6**	**34**		

The decrease in potential FLI for gentle slopes and valleys with increased canopy fuel seems counterintuitive. However, since FlamMap calculates FLI as combustion rate × flame depth while flame depth is fire rate of spread × residence time, the decrease is likely related to the effects of denser canopy resulting in lower mid-flame windspeed and spread rate and to higher humidity and fuel moisture causing a lower combustion rate (Agee et al., 2000; Rothermel, 1983). In actual wildfires, canopy fuel reductions from treatments have indeed resulted in increased FLI and spread rates (Cochrane et al., 2012). In California, higher fuel moistures in areas with canopy shading are limited to early in the fire season because any shade related moisture differences disappear as the dry season progresses (Estes et al., 2012).

In the LAVO landscape, valley bottoms had more passive crown fire and greater increases in FLI when surface fuels increased than did gentle slopes. This is because in LAVO, the LMU designated valley bottoms have, on average, a greater slope angle than the predominately flat areas comprising the gentle slope categories, and because the modeled gridded winds were funneled through the valleys. The tendency of valleys and gentler slopes to burn at lower severity has been shown to maintain areas with high canopy cover and large trees providing persistent refugia of animal habitat and plant seed sources (Krawchuk et al., 2016). Although these topographic positions exhibit greater resilience to fuel build-up than slopes and ridges, excessive fuel build-up may overwhelm terrain controls, leading to historically unusual fire behavior, potential novel vegetation, and legacy effects that drive future vegetation dynamics (See Fig. 3) (Bradstock et al., 2010; García-Llamas et al., 2020).

5.2. *Weather and fuel changes*

Weather during actual wildfires in LAVO exceeded percentile weather conditions which has also occurred in other wildfires in the region (Jain et al., 2017). The increasing likelihood of extreme weather is an incentive for including extreme conditions in planning exercises. In gentle terrain, extreme weather may drive stronger shifts in fire behavior even when surface fuel loads are not high. Relative increases in FLI between percentile and actual fire weather were greatest on gentle slopes. This has implications for how different landscapes with a history of fire exclusion are likely to respond to fires in a changing climate. For example, in the rolling topography on Arizona's Kaibab Plateau, modeled fire severity in forests restored to historical composition, density, and age structure was insufficient to prevent high severity fire spreading from mid to high elevations under climate change weather scenarios (Flatley and Fulé, 2016). In contrast, in the more complex terrain of the Sierra Nevada, with 1200 m of elevation change, a range of modeled fuels reduction treatments all reduced fire severity even in extreme conditions (Dow et al., 2016). Gentle topography may partially explain findings that weather is a stronger predictor of fire severity than topography in the Columbia and Colorado Plateaus regions of the western USA (Parks et al., 2018). Because of the relative importance of weather, long-term landscape and fire regime restoration strategies in gentler landscapes may especially benefit from incorporating projected climate change in evaluating likely effectiveness.

5.3. *Model limitations*

This study has several limitations related to the modeling platform and data streams used to project fire behavior. First, developing accurate estimates of pre-fire exclusion canopy fuels is challenging. Our values are based on forest reconstructions using tree rings and yield estimates of forest structure similar to early 20th century forest inventory values (Scholl and Taylor, 2010) and another historical forest reconstruction (Brown et al., 2008). However, reconstructions are developed from a limited set of forest conditions and may underestimate the abundance of small diameter trees and regeneration (Taylor et al., 2014). This would in turn over-estimate the CBH which would over-estimate surface fire component since FlamMap's torching simulation is highly sensitive to CBH (Scott and Reinhardt, 2001). Most of these forests would have had a patchy distribution of regeneration that could affect local canopy fuel conditions and contribute to a patchy distribution of potential crown fire. To help address this limitation, in addition to crown fire, we also compared changes in FLI which does not rely on CBH. Moreover, we focused on relative differences in fire behavior rather than actual values to highlight where contemporary conditions deviate from those before fire exclusion.

Second, the model results rely on FlamMap's treatment of surface fuel models (Cruz and Alexander 2010) and their linkage to canopy fuel characteristics and potential for crown fire behavior. The contemporary surface fuel model map in LAVO was derived from an extensive set of field measurements of forest characteristics. The projected fire behavior in FlamMap using the LAVO data set was more similar to observed wildfire effects than when LANDFIRE data was used (Pierce et al., 2012). There is some evidence that fire modeling systems such as FlamMap may under-predict potential for crown fire behavior in coniferous forests in the western USA (Cruz and Alexander, 2010).

Third, fire behavior models generally do not incorporate larger diameter (1000 h) surface fuels into fire behavior estimates. Accumulations of large woody fuels can have a significant effect on fire intensity

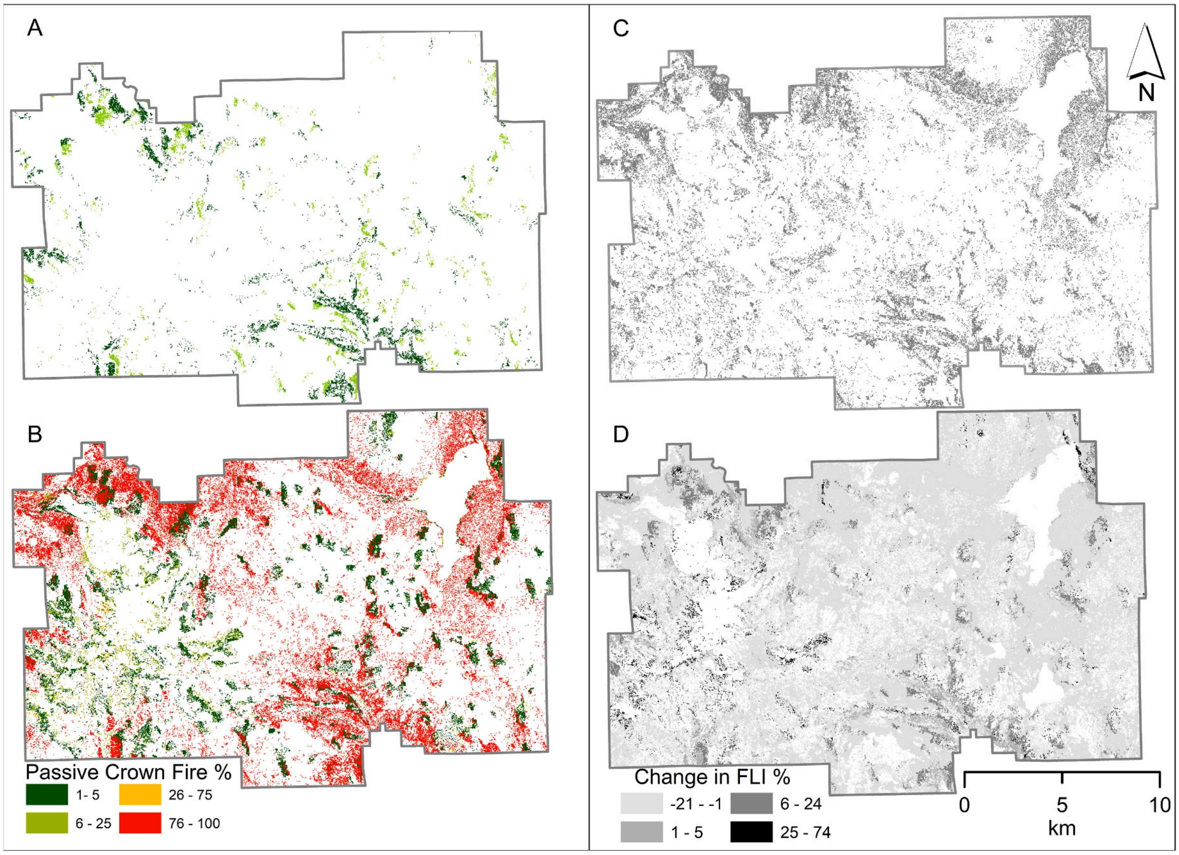

Fig. 5. Percentage of passive crown fire predicted for actual fire weather conditions with current (year 2000) surface fuel loads in Lassen Volcanic National Park, CA and A. pre-exclusion or B. contemporary canopy fuel estimates. C. locations in black where passive crown fire was not predicted for pre-exclusion but possible under contemporary conditions D. Percent change in fire-line intensity from pre-exclusion to contemporary canopy fuel scenarios.

and resulting severity (Stephens et al., 2018). Incorporating these fuels into modeling systems could influence the results, and, for example, diminish some of the decrease in FLI observed on gentle slope and valleys with higher fuel loads.

Lastly, while FlamMap is useful for estimating how different stands in a landscape would burn and describing potential patterns of intensity, it does not model how various fires would likely spread through the landscape as does, for example, FarSite (Finney, 1998). Fire spread simulations may be valuable in developing long-term management strategies to target fuel reduction in locations with the greatest effects on reducing the potential for large high-intensity fires.

5.4. Management implications

The growing futility of efforts to minimize fire extent in California and other semi-arid forests across the globe is becoming clear. Calls for a paradigm shift to focus instead on managing fuels and fire severity are growing (Moreira et al., 2020; North et al., 2015; Stephens et al., 2020). Classifying forest structure in terms of crown fire potential can help define fuel transition points in different forest types. A greater sensitivity of steep slopes and ridgetops to increased fuels and more severe fire effects has been noted in ecosystems beyond LAVO including in SE Australia's sclerophyll forests (Bradstock et al., 2010) and northern Spain's *Pinus halepensis* forests (Ruiz-González and Álvarez-González, 2011). This suggests there may be an overall greater sensitivity of these topographic positions to fuel accumulation caused by fire free periods much longer than HRV.

Our findings in LAVO show the greatest increase in FLI and crown type fire behavior were concentrated in the northern and southern-most portions of the park. In these areas, where fuel increases on ridges and steep slopes approach TPC, applying prescribed fire or using wildfires burning under moderate conditions (i.e., Estes et al., 2017) to consume fuels would reduce landscape fire hazard. Our modeling shows that ridges and steep slopes reach TPC with surface fuels represented by fuel models TU5 to TL8. Targeting ridges and steep slopes, and even gentle slopes and valley bottoms that reach TU5 to TL8, would reduce potential crown type fire behavior across the landscape and reduce fuels and fire behavior towards HRV. A focus on fuel reduction in locations prone to crown fire would greatly enhance the treatment effectiveness by also decreasing the probability of spotting which strongly influences fire spread rate (Cochrane et al., 2012). Feathering treatments at boundaries between terrain units could also promote development of landscape compartments with similar fire regimes (i.e. frequency, severity) that can be offset in time reducing potential of landscape fire spread that has been observed in some pre-fire exclusion landscapes (Taylor and Skinner, 2003).

Management effectiveness in the long term will require periodic retreatment with fire to consume fuels as they accumulate and maintain lower FLI and potential for crown fire behavior. The longevity of the effectiveness of fuel reduction against crown fire potential is quite variable across ecosystems, ranging from decades in fire-prone forests in the western USA (Pawlikowski et al., 2019) to under five years in SE Australia schlerophyll forests (Bradstock et al., 2010)**.** Our modeling suggests that fuel thresholds for achieving desirable reduction in fire behavior do not have to be as low as historical fuel loads for surface fire to remain predominant across LAVO. In our simulations, crown fire appeared on the landscape between fuel loads TL3 to TL4. Others have shown fire behavior reduction may be achieved with modest fuel decreases (Schmidt et al., 2008).

6. Conclusions

This study advances understanding of how topography and fuels interact to cause changes in potential fire behavior with fire exclusion. As fuels accumulate, historical topography-fuel feedbacks diminish, and fire behavior becomes more driven by fuels and weather. Moreover, fire weather during recent wildfires created more extreme modeled fire behavior than percentile conditions suggesting higher potential for large areas of crown type fire behavior and long-term vegetation changes caused by severe fire effects. Equivalent fuel loads exhibited different fire behavior depending on topographic characteristics. Fire behavior was more extreme on steep slopes and ridges compared to gentle slopes and valleys, particularly as fuels increased to intermediate loads. Our study demonstrates the value to landscape management strategies of identifying fuel TPCs by topographic units. This can help prioritize use of limited resources before or during the next wildfire to achieve maximum effect.

Author statement

Catherine Airey-Lauvaux: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft, Writing review and analysis, Visualization. Andrew Pierce: Conceptualization, Methodology, Investigation, Writing – original draft, Formal analysis, Funding acquisition, Visualization. Carl Skinner: Conceptualization, Methodology, Writing – review & editing. Alan Taylor: Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing, Funding acquisition, Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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References

Abatzoglou, J.T., Williams, A.P., 2016. Impact of anthropogenic climate change on wildfire across western US forests. Proc. Natl. Acad. Sci. Unit. States Am. 113 (42), 11770–11775. https://doi.org/10.1073/pnas.1607171113.

Agee, J.K., 1993. Fire Ecology of Pacific Northwest Forests. Island Press. http://catalog.hathitrust.org/Record/002806216.

Agee, J.K., Skinner, C.N., 2005. Basic principles of forest fuel reduction treatments. For. Ecol. Manag. 211 (1–2), 83–96. https://doi.org/10.1016/j.foreco.2005.01.034.

Agee, J.K., Bahro, B., Finney, M.A., Omi, P.N., Sapsis, D.B., Skinner, C.N., Van Wagtendonk, J.W., Weatherspoon, C.P., 2000. The use of shaded fuelbreaks in landscape fire management. For. Ecol. Manag. 127 (1–3), 55–66. https://doi.org/10.1016/S0378-1127(99)00116-4.

Albini, F.A., 1976. Computer-based Models of Wildland Fire Behavior: A User's Manual. Intermountain Forest and Range Experiment Station, Forest Service, US.

Alexander, M.E., Cruz, M., 2019. Fireline Intensity. *Encyclopedia of Wildfires and Wildland-Urban Interface (WUI) Fires*. Springer, Berlin/Heidelberg, Germany. https://doi.org/10.1007/978-3-319-51727-8.

Barnett, K., Parks, S.A., Miller, C., Naughton, H.T., 2016. Beyond fuel treatment effectiveness: characterizing interactions between fire and treatments in the US. Forests 7 (10), 237. https://doi.org/10.3390/f7100237.

Bradshaw, L., Tirmenstein, D., 2010. FireFamilyPlus users guide, version 4.1 (Draft). USDA Forest Service, Fire Sciences Laboratory. https://www.firelab.org/sites/default/files/images/downloads/FFP-4_1_Draft_Users_Guide_0.pdf.

Bradstock, R.A., Hammill, K.A., Collins, L., Price, O., 2010. Effects of weather, fuel and terrain on fire severity in topographically diverse landscapes of south-eastern Australia. Landsc. Ecol. 25 (4), 607–619. https://doi.org/10.1007/s10980-009-9443-8.

Brown, P.M., Wienk, C.L., Symstad, A.J., 2008. Fire and forest history at Mount Rushmore. Ecol. Appl. 18 (8), 1984–1999. https://doi.org/10.1890/07-1337.1.

Calkin, D.E., Cohen, J.D., Finney, M.A., Thompson, M.P., 2014. How risk management can prevent future wildfire disasters in the wildland-urban interface. Proc. Natl. Acad. Sci. Unit. States Am. 111 (2), 746–751. https://doi.org/10.1073/pnas.1315088111.

Cochrane, M., Moran, C., Wimberly, M., Baer, A., Finney, M.A., Beckendorf, K., Eidenshink, J., Zhu, Z., 2012. Estimation of wildfire size and risk changes due to fuels treatments. Int. J. Wildland Fire 21 (4), 357–367. https://doi.org/10.1071/WF11079.

Cohen, J., 2008. The wildland-urban interface fire problem: a consequence of the fire exclusion paradigm. For. Hist. Today Fall 20–26, 20–26.

Collins, B.M., 2014. Fire weather and large fire potential in the northern Sierra Nevada. Agric. For. Meteorol. 189–190, 30–35. https://doi.org/10.1016/j.agrformet.2014.01.005.

Coop, J.D., Parks, S.A., McClernan, S.R., Holsinger, L.M., 2016. Influences of prior wildfires on vegetation response to subsequent fire in a reburned Southwestern landscape. Ecol. Appl. 26 (2), 346–354. https://doi.org/10.1890/15-0775.

Covington, W., Moore, M., 1994. Postsettlement changes in natural fire regimes and forest structure: ecological restoration of old-growth ponderosa pine forests. J. Sustain. For. 2 (1–2), 153–181. https://doi.org/10.1300/J091v02n01_07.

Cruz, M.G., Alexander, M.E., 2010. Assessing crown fire potential in coniferous forests of western North America: A critique of current approaches and recent simulation studies. Int. J. Wildland Fire 19 (4), 377–398. https://doi.org/10.1071/WF08132.

Davis, K.T., Higuera, P.E., Sala, A., 2018. Anticipating fire-mediated impacts of climate change using a demographic framework. Funct. Ecol. 32 (7), 1729–1745. https://doi.org/10.1111/1365-2435.13132.

Dillon, G.K., Holden, Z.A., Morgan, P., Gregg, M.A., Heyerdahl, E.K., Luce, C.H., 2011. Both topography and climate affected forest and woodland burn severity in two regions of the western US, 1984 to 2006. Ecosphere 2 (12), art130. https://doi.org/10.1890/ES11-00271.1.

Dow, C.B., Collins, B.M., Stephens, S.L., 2016. Incorporating resource protection constraints in an analysis of landscape fuel-treatment effectiveness in the northern Sierra Nevada, CA, USA. Environ. Manag. 57 (3), 516–530. https://doi.org/10.1007/s00267-015-0632-8.

Estes, B.L., Knapp, E.E., Skinner, C.N., Miller, J.D., Preisler, H.K., 2017. Factors influencing fire severity under moderate burning conditions in the Klamath Mountains, northern California, USA. Ecosphere 8 (5), e01794. https://doi.org/10.1002/ecs2.1794.

Estes, B.L., Knapp, E.E., Skinner, C.N., Uzoh, F.C., 2012. Seasonal variation in surface fuel moisture between unthinned and thinned mixed conifer forest, northern California, USA. Int. J. Wildland Fire 21 (4), 428–435. https://doi.org/10.1071/WF11056.

FAM, [Fire, Aviation Management], 2011. FAM-IT Portal, Fire and Weather Data. https://famit.nwcg.gov/applications/FireAndWeatherData.

Finney, M.A., 1998. FARSITE, Fire Area Simulator—Model Development and Evaluation. US Department of Agriculture, Forest Service, Rocky Mountain Research Station. https://doi.org/10.2737/RMRS-RP-4. Issue 4.

Finney, M.A., 2006. An Overview of FlamMap Fire Modeling Capabilities, vol. 41. https://www.fs.usda.gov/treesearch/pubs/25948.

Flatley, W.T., Fulé, P.Z., 2016. Are historical fire regimes compatible with future climate? Implications for forest restoration. Ecosphere 7 (10), e01471. https://doi.org/10.1002/ecs2.1471.

Forthofer, J., Shannon, K., Butler, B., Kalispell, M.T., 2009. Simulating diurnally driven slope winds with WindNinja. In: Proceedings of 8th Eighth Symposium on Fire and Forest Meteorology; 2009 October 13-15. American Meteorological Society, Boston, MA, p. 13. Online: https://ams.confex.com/ams/8Fire/techprogram/paper_156275.htm.

Fulé, P.Z., Crouse, J.E., Cocke, A.E., Moore, M.M., Covington, W.W., 2004. Changes in canopy fuels and potential fire behavior 1880–2040: Grand Canyon, Arizona. Ecol. Modell. 175 (3), 231–248. https://doi.org/10.1016/j.ecolmodel.2003.10.023.

Fulé, P.Z., Korb, J.E., Wu, R., 2009. Changes in forest structure of a mixed conifer forest, southwestern Colorado, USA. For. Ecol. Manag. 258 (7), 1200–1210. https://doi.org/10.1016/j.foreco.2009.06.015.

García-Llamas, P., Suárez-Seoane, S., Fernández-Manso, A., Quintano, C., Calvo, L., 2020. Evaluation of fire severity in fire prone ecosystems of Spain under two different environmental conditions. J. Environ. Manag. 271, 110706. https://doi.org/10.1016/j.jenvman.2020.110706.

Hessburg, P.F., Agee, J., Franklin, J., 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 (1–2), 117–139. https://doi.org/10.1016/j.foreco.2005.02.016.

Hessburg, P.F., Churchill, D.J., Larson, A.J., Haugo, R.D., Miller, C., Spies, T.A., North, M.P., Povak, N.A., Belote, R.T., Singleton, P.H., 2015. Restoring fire-prone Inland Pacific landscapes: Seven core principles. Landsc. Ecol. 30 (10), 1805–1835. https://doi.org/10.1007/s10980-015-0218-0.

Hessburg, P.F., Miller, C.L., Parks, S.A., Povak, N.A., Taylor, A.H., Higuera, P.E., Prichard, S.J., North, M.P., Collins, B.M., Hurteau, M.D., 2019. Climate, environment, and disturbance history govern resilience of western North American forests. Front. Ecol. Evol. 7, 239. https://doi.org/10.3389/fevo.2019.00239.

Hurteau, M.D., North, M.P., Koch, G.W., Hungate, B.A., 2019. Opinion: managing for disturbance stabilizes forest carbon. Proc. Natl. Acad. Sci. Unit. States Am. 116 (21), 10193–10195. https://doi.org/10.1073/pnas.1905146116.

Jain, P., Wang, X., Flannigan, M.D., 2017. Trend analysis of fire season length and extreme fire weather in North America between 1979 and 2015. Int. J. Wildland Fire 26 (12), 1009–1020. https://doi.org/10.1071/WF17008.

Kane, V.R., Cansler, C.A., Povak, N.A., Kane, J.T., McGaughey, R.J., Lutz, J.A., Churchill, D.J., North, M.P., 2015. Mixed severity fire effects within the Rim fire: relative importance of local climate, fire weather, topography, and forest structure. For. Ecol. Manag. 358, 62–79. https://doi.org/10.1016/j.foreco.2015.09.001.

Keane, R.E., Agee, J., Fule, P.Z., Keeley, J.E., Key, C., Kitchen, S.G., Miller, R., Schulte, L. A., 2008. Ecological effects of large fires on US landscapes: Benefit or catastrophe? Int. J. Wildland Fire 17, 696–712. https://doi.org/10.1071/WF07148.

Keane, R.E., Loehman, R.A., Holsinger, L.M., Falk, D.A., Higuera, P., Hood, S.M., Hessburg, P.F., 2018. Use of landscape simulation modeling to quantify resilience for ecological applications. Ecosphere 9 (9). https://doi.org/10.1002/ecs2.2414.

Knapp, E.E., Keeley, J.E., 2006. Heterogeneity in fire severity within early season and late season prescribed burns in a mixed-conifer forest. Int. J. Wildland Fire 15 (1), 37–45. https://doi.org/10.1071/WF04068.

Knapp, E.E., Bernal, A.A., Kane, J.M., Fettig, C.J., North, M.P., 2021. Variable thinning and prescribed fire influence tree mortality and growth during and after a severe drought. For. Ecol. Manag. 479, 118595. https://doi.org/10.1016/j.foreco.2020.118595.

Krawchuk, M.A., Haire, S.L., Coop, J., Parisien, M., Whitman, E., Chong, G., Miller, C., 2016. Topographic and fire weather controls of fire refugia in forested ecosystems of northwestern North America. Ecosphere 7 (12), e01632. https://doi.org/10.1002/ecs2.1632.

Lecina-Diaz, J., Alvarez, A., Retana, J., 2014. Extreme fire severity patterns in topographic, convective and wind-driven historical wildfires of Mediterranean pine forests. PLoS One 9 (1), e85127. https://doi.org/10.1371/journal.pone.0085127.

Lydersen, J.M., Collins, B.M., 2018. Change in vegetation patterns over a large forested landscape based on historical and contemporary aerial photography. Ecosystems 21 (7), 1348–1363. https://doi.org/10.1007/s10021-018-0225-5.

Lydersen, J.M., Collins, B.M., Brooks, M.L., Matchett, J.R., Shive, K.L., Povak, N.A., Kane, V.R., Smith, D.F., 2017. Evidence of fuels management and fire weather influencing fire severity in an extreme fire event. Ecol. Appl. 27 (7), 2013–2030. https://doi.org/10.1002/eap.1586.

Merschel, A.G., Heyerdahl, E.K., Spies, T.A., Loehman, R.A., 2018. Influence of landscape structure, topography, and forest type on spatial variation in historical fire regimes, Central Oregon, USA. Landsc. Ecol. 33 (7), 1195–1209. https://doi.org/10.1007/s10980-018-0656-6.

Miller, J.D., Safford, H.D., Crimmins, M., Thode, A.E., 2009. Quantitative evidence for increasing forest fire severity in the Sierra Nevada and southern Cascade Mountains, California and Nevada, USA. Ecosystems 12 (1), 16–32. https://doi.org/10.1007/s10021-008-9201-9.

Mitsopoulos, I., Chrysafi, I., Bountis, D., Mallinis, G., 2019. Assessment of factors driving high fire severity potential and classification in a Mediterranean pine ecosystem. J. Environ. Manag. 235, 266–275. https://doi.org/10.1016/j.jenvman.2019.01.056.

Moreira, F., Ascoli, D., Safford, H., Adams, M.A., Moreno, J.M., Pereira, J.M., Catry, F.X., Armesto, J., Bond, W., González, M.E., 2020. Wildfire management in Mediterranean-type regions: Paradigm change needed. Environ. Res. Lett. 15 (1), 011001 https://doi.org/10.1088/1748-9326/ab541e.

Morgan, P., 2004. Back to the Future: the Value of History in Understanding and Managing Dynamic Landscapes. USDA Forest Service General Technical Report PNW, pp. 78–86.

Moritz, M.A., Hurteau, M.D., Suding, K.N., D'Antonio, C.M., 2013. Bounded ranges of variation as a framework for future conservation and fire management. Ann. N. Y. Acad. Sci. 1286 (1), 92–107. https://doi.org/10.1111/nyas.12104.

National Park Service, 2006. Management Policies. National Park Service. https://www.nps.gov/policy/MP_2006.pdf.

NOHRSC [National Operational Hydrologic Remote Sensing Center], 2010. Snow Data Assimilation System (SNODAS) Data Products at NSIDC. National Snow and Ice Data Center, Boulder, CO. https://nsidc.org/data/g02158.

North, M., Stine, P., O'Hara, K., Zielinski, W., Stephens, S., 2009. An Ecosystem Management Strategy for Sierran Mixed-Conifer Forests, vol. 49. US Department of Agriculture, Forest Service, Pacific Southwest Research Station, Albany, CA, p. 220. Gen. Tech. Rep. PSW-GTR-220 (Second Printing, with Addendum). https://www.fs.fed.us/psw/publications/documents/psw_gtr220/.

North, M., Collins, B.M., Stephens, S., 2012. Using fire to increase the scale, benefits, and future maintenance of fuels treatments. J. For. 110 (7), 392–401. https://doi.org/10.5849/jof.12-021.

North, M., Brough, A., Long, J., Collins, B., Bowden, P., Yasuda, D., Miller, J., Sugihara, N., 2015. Constraints on mechanized treatment significantly limit mechanical fuels reduction extent in the Sierra Nevada. J. For. 113 (1), 40–48. https://doi.org/10.5849/jof.14-058.

O'Connor, C.D., Falk, D.A., Lynch, A.M., Swetnam, T.W., 2014. Fire severity, size, and climate associations diverge from historical precedent along an ecological gradient in the Pinaleño Mountains, Arizona, USA. For. Ecol. Manag. 329, 264–278. https://doi.org/10.1016/j.foreco.2014.06.032.

Parker, A.J., 1991. Forest/Environment Relationships in Lassen Volcanic National Park, California, U.S.A. J. Biogeogr. 18 (5), 543–552. https://doi.org/10.2307/2845690.

Parks, S.A., Holsinger, L.M., Panunto, M.H., Jolly, W.M., Dobrowski, S.Z., Dillon, G.K., 2018. High-severity fire: Evaluating its key drivers and mapping its probability across western US forests. Environ. Res. Lett. 13 (4), 044037 https://doi.org/10.1088/1748-9326/aab791.

Pawlikowski, N.C., Coppoletta, M., Knapp, E., Taylor, A.H., 2019. Spatial dynamics of tree group and gap structure in an old-growth ponderosa pine-California black oak forest burned by repeated wildfires. For. Ecol. Manag. 434, 289–302. https://doi.org/10.1016/j.foreco.2018.12.016.

Pierce, A.D., Farris, C.A., Taylor, A.H., 2012. Use of random forests for modeling and mapping forest canopy fuels for fire behavior analysis in Lassen Volcanic National Park, California, USA. For. Ecol. Manag. 279, 77–89. https://doi.org/10.1016/j.foreco.2012.05.010.

Prichard, S.J., Povak, N.A., Kennedy, M.C., Peterson, D.W., 2020. Fuel Treatment Effectiveness in the Context of Landform, Vegetation, and Large, Wind-driven Wildfires. Ecological Applications, e02104. https://doi.org/10.1002/eap.2104.

Ritchie, M.W., Skinner, C.N., Hamilton, T.A., 2007. Probability of tree survival after wildfire in an interior pine forest of northern California: Effects of thinning and prescribed fire. For. Ecol. Manag. 247 (1–3), 200–208. https://doi.org/10.1016/j.foreco.2007.04.044.

Rollins, M.G., Morgan, P., Swetnam, T., 2002. Landscape-scale controls over 20 th century fire occurrence in two large Rocky Mountain (USA) wilderness areas. Landsc. Ecol. 17 (6), 539–557.

Rothermel, R.C., 1983. How to predict the spread and intensity of forest and range fires. USDA, Forest Service, Intermountain Forest and Range Experiment Station. General Technical Report INT-143, 161 pp.

Ruiz-González, A.D., Álvarez-González, J.G., 2011. Canopy bulk density and canopy base height equations for assessing crown fire hazard in Pinus radiata plantations. Can. J. For. Res. 41 (4), 839–850. https://doi.org/10.1139/x10-237.

Safford, H.D., Schmidt, D.A., Carlson, C.H., 2009. Effects of fuel treatments on fire severity in an area of wildland–urban interface, Angora Fire, Lake Tahoe Basin, California. For. Ecol. Manag. 258 (5), 773–787. https://doi.org/10.1016/j.foreco.2009.05.024.

Schmidt, D.A., Taylor, A.H., Skinner, C.N., 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. https://doi.org/10.1016/j.foreco.2008.01.023.

Schoenherr, A.A., 2017. *A natural history of California*. Univ of California Press.doi: 10.1525/9780520964556.

Scholl, A.E., Taylor, A.H., 2010. Fire regimes, forest change, and self-organization in an old-growth mixed-conifer forest, Yosemite National Park, USA. Ecol. Appl. 20 (2), 362–380. https://doi.org/10.1890/08-2324.1.

Scott, J., Burgan, R., 2005. Standard fire behavior fuel models: A comprehensive set for use with Rothermel's surface fire spread model. Gen. Tech. Report RMRS-GTR-153. USDA Forest Service, Fort Collins, CO. https://doi.org/10.2737/RMRS-GTR-153.

Scott, J., Reinhardt, E., 2001. Assessing Crown Fire Potential by Linking Models of Surface and Crown Fire Behavior. USDA Forest Service Res. https://doi.org/10.2737/RMRS-RP-29. *Pap.* RMRS-RP-29.

Skinner, C.N., Taylor, A.H., 2018. Southern Cascades bioregion. In: Sugihara, N., van Wagtendonk, J.W., Fites-Kaufman, J., Shaffer, K.E., Thode, A.E. (Eds.), *Fire in California's ecosystems*, 2nd edition, revised. University of California Press, pp. 195–218. https://doi.org/10.1525/9780520961913-015.

Skinner, C.N., Taylor, A.H., Agee, J.K., Briles, C.E., Whitlock, C.L., 2018. Klammath mountains bioregion. In: Sugihara, N., van Wagtendonk, J.W., Fites-Kaufman, J., Shaffer, K.E., Thode, A.E. (Eds.), *Fire in California's ecosystems*, 2nd edition, revised. University of California Press, pp. 171–193. https://doi.org/10.1525/9780520961913-014.

Spies, T.A., Hemstrom, M.A., Youngblood, A., Hummel, S., 2006. Conserving Old-Growth Forest Diversity in Disturbance-Prone Landscapes. Conserv. Biol. 20 (2), 351–362. https://doi.org/10.1111/j.1523-1739.2006.00389.x.

Steel, Z.L., Safford, H.D., Viers, J.H., 2015. The fire frequency-severity relationship and the legacy of fire suppression in California forests. Ecosphere 6 (1), 1–23. https://doi.org/10.1890/ES14-00224.1.

Stephens, S.L., Collins, B.M., Fettig, C.J., Finney, M.A., Hoffman, C.M., Knapp, E.E., North, M.P., Safford, H., Wayman, R.B., 2018. Drought, Tree Mortality, and Wildfire in Forests Adapted to Frequent Fire. Bioscience 68 (2), 77–88. https://doi.org/10.1093/biosci/bix146.

Stephens, S.L., Westerling, A.L., Hurteau, M.D., Peery, M.Z., Schultz, C.A., Thompson, S., 2020. Fire and climate change: Conserving seasonally dry forests is still possible. Front. Ecol. Environ. 18 (6), 354–360. https://doi.org/10.1002/fee.2218.

Stratton, R.D., 2006. Guidance on spatial wildland fire analysis: Models, tools, and techniques, 15. US Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO, p. 183. https://doi.org/10.2737/RMRS-GTR-183. Gen. Tech. Rep. RMRS-GTR-183.

Sturtevant, B.R., Scheller, R.M., Miranda, B.R., Shinneman, D., Syphard, A., 2009. Simulating dynamic and mixed-severity fire regimes: A process-based fire extension for LANDIS-II. Ecol. Model. 220 (23), 3380–3393. https://doi.org/10.1016/j.ecolmodel.2009.07.030.

Syphard, A.D., Scheller, R.M., Ward, B.C., Spencer, W.D., Strittholt, J.R., 2011. Simulating landscape-scale effects of fuels treatments in the Sierra Nevada, California, USA. Int. J. Wildland Fire 20 (3), 364–383. https://doi.org/10.1071/WF09125.

Taylor, A.H., 1990. Tree invasion in meadows of Lassen Volcanic national park, California. Prof. Geogr. 42 (4), 457–470. https://doi.org/10.1111/j.0033-0124.1990.00457.x.

Taylor, A.H., 1995. Forest expansion and climate change in the mountain hemlock (Tsuga mertensiana) zone, Lassen Volcanic National Park, California, USA. Arct. Alp. Res. 207–216. https://doi.org/10.2307/1551951.

Taylor, A.H., 2000. Fire Regimes and Forest Changes in Mid and Upper Montane Forests of the Southern Cascades, Lassen Volcanic National Park, California, U.S.A. J. Biogeogr. 27 (1), 87–104. https://doi.org/10.1046/j.1365-2699.2000.00353.x.

Taylor, A.H., Skinner, C.N., 2003. Spatial patterns and controls on historical fire regimes and forest structure in the Klamath Mountains. Ecol. Appl. 13 (3), 704–719. https://doi.org/10.1890/1051-0761%282003%29013%5B0704%3ASPACOH%5D2.0.CO%3B.

Taylor, A.H., Vandervlugt, A.M., Maxwell, R.S., Beaty, R.M., Airey, C., Skinner, C.N., 2014. Changes in forest structure, fuels and potential fire behaviour since 1873 in the Lake Tahoe Basin, USA. Appl. Veg. Sci. 17 (1), 17–31. https://doi.org/10.1111/avsc.12049.

Twidwell, D., Wonkka, C.L., Wang, H.-H., Grant, W.E., Allen, C.R., Fuhlendorf, S.D., Garmestani, A.S., Angeler, D.G., Taylor Jr., C.A., Kreuter, U.P., 2019. Coerced resilience in fire management. J. Environ. Manag. 240, 368–373. https://doi.org/10.1016/j.jenvman.2019.02.

Underwood, E.C., Viers, J.H., Quinn, J.F., North, M., 2010. Using topography to meet wildlife and fuels treatment objectives in fire-suppressed landscapes. Environ. Manag. 46 (5), 809–819. https://doi.org/10.1007/s00267-010-9556-5.

Vernon, M.J., Sherriff, R.L., van Mantgem, P., Kane, J.M., 2018. Thinning, tree-growth, and resistance to multi-year drought in a mixed-conifer forest of northern California. For. Ecol. Manag. 422, 190–198. https://doi.org/10.1016/j.foreco.2018.03.043.

Westerling, A.L., 2016. Increasing western US forest wildfire activity: Sensitivity to changes in the timing of spring. Phil. Trans. Biol. Sci. 371 https://doi.org/10.1098/rstb.2015.0178, 1696.

Williams, A.P., Abatzoglou, J.T., Gershunov, A., Guzman-Morales, J., Bishop, D.A., Balch, J.K., Lettenmaier, D.P., 2019. Observed Impacts of Anthropogenic Climate Change on Wildfire in California. Earth's Future 7 (8), 892–910. https://doi.org/10.1029/2019EF001210.

WRCC [Western Regional Climate Center], 2011. Manzanita Lake, California, Period of Record. http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?ca5311.