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Forest stand and site characteristics influence fuel consumption in repeat prescribed burns

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Abstract. Prescribed fire is a vital tool for mitigating wildfire hazard and restoring ecosystems in many western North American forest types. However, there can be considerable variability in fuel consumption from prescribed burns, which affects both hazard mitigation and emissions. In the present study, data from replicated, repeat-entry burns following a period of 100+ years of fire exclusion were used to provide a detailed quantification of fuel consumption as it varies by fuel type, size class, stand and prescribed burn number (first, second or third). Using model selection on a series of linear mixed-effects models, it was determined that total fuel load, proportion of overstorey pine, slope, canopy cover, basal area of live trees, burn number and stand influenced fuel consumption at a 0.04-ha scale. Specifically, overstorey pine composition had a positive effect on fuel consumption. Overall fuel consumption across the three burns averaged 45% of pre-burn fuel loads. Overall consumption was highest for the first burn at 65%, decreasing by 15–20% with each successive burn number. Fuel consumption was highly variable by fuel type, stand and tree species composition. This variability may be advantageous for managers seeking to foster structural diversity and resilience in forest stands.

Additional keywords: fire behaviour, fuel modelling, fuel reduction.

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Introduction

Over the past century, reduction of Indigenous burning and aggressive fire suppression drastically altered forest structure in many forest types throughout western North America (Parsons and Debenedetti 1979; Hessburg *et al.* 2005; Brown *et al.* 2008; Naficy *et al.* 2010; Taylor *et al.* 2014). This effect is especially pronounced in relatively productive forests that were historically adapted to frequent fire. The mixed-conifer forests of the Sierra Nevada fit this description, with mean historical fire-return intervals ranging between 11 and 16 years (Van de Water and Safford 2011; North *et al.* 2016). In the absence of fire, modern forests are characterised by greater fuel loads, more horizontal and vertical fuel continuity, increased tree density, smaller average tree diameter and a shift in composition towards shade-tolerant species (Miller and Urban 2000; Naficy *et al.* 2010; Scholl and Taylor 2010; Stephens *et al.* 2015). The sum effect of these changes is a marked increase in the risk of high-severity wildfire (Taylor *et al.* 2014), which is manifested in increased proportions of high-severity effects and larger, more simply shaped contiguous patches of high severity (Miller *et al.* 2009; Stevens *et al.* 2017). These fires have resulted in unprecedented property damage, injury and human death (Cal Fire 2018), prompting federal, state and local governments to allocate hundreds of millions of dollars to forest treatments in an effort to reduce fire hazard in forests across California.

Prescribed fire is a vital treatment tool for mitigating fire hazard in forests historically adapted to frequent fire (Fernandes and Botelho 2003; Burrows and McCaw 2013; Ryan *et al.* 2013; Little Hoover Commission 2018; Cal Fire 2019; Stephens *et al.* 2019). Specifically, it mimics the function of natural fire occurrence before Anglo-European settlement by altering stand structure and fuel bed characteristics (Biswell 1989; Stephenson 1999). However, fuel consumption in prescribed fires can be highly variable. Fuel consumption is dependent on both prescription parameters (fuel moisture, weather, firing technique) and measurable stand characteristics (fuel bed structure and composition, overstorey density, topography). Although the influence of prescription parameters is fairly well understood, the influence of stand characteristics is not (Kauffman and Martin 1988; Miyanishi 2001; Knapp *et al.* 2005; Vaillant *et al.* 2009). At best, previous studies have considered the effects of one or two fuel bed or stand characteristics on prescribed-fire fuel consumption (Kauffman and Martin 1988; Knapp *et al.* 2005). An improved understanding of the role of stand characteristics in fuel consumption can help forest managers anticipate the effects of burns, especially because heterogeneity is increasingly emphasised as a desired outcome for forest restoration (North *et al.* 2009).

Moreover, previous analyses of fuel consumption fail to consider instances of repeat burns, instead focusing on first-entry burns occurring in areas that have experienced many decades without fire (Kauffman and Martin 1988; Stephens and Finney 2002; Knapp *et al.* 2005; Vaillant *et al.* 2009). First-entry burns, defined as prescribed burns carried out after an extended period with no fire events, are important for 'reclaiming' fire on a site, i.e. returning a fundamental ecosystem process to a forest that has long been fire-excluded (Biswell 1989). However, repeated burns, performed at somewhat regular intervals, are necessary to achieve long-term desired forest and fuel structures (Webster and Halpern 2010). An estimated 2.4 million ha of forestland in the Sierra Nevada alone are in 'dire need of restoration' (Little Hoover Commission 2018: p. 20). Prescribed fire will be needed to address a substantial portion of this restoration deficit, because mechanised forest restoration can be limited by several constraints (e.g. access and operability, funding, land designation) (North *et al.* 2015). As the scale of prescribed-fire use increases, so will the proportion of prescribed fires that are repeat burns. Furthermore, repeat burns are likely to exhibit patterns of fuel consumption different from the initial burn. For example, initial burns may consume heavy accumulations of surface and ground fuel, but they are also likely to result in a pulse of woody surface fuel input from mortality of small- to mid-sized trees (Stephens and Moghaddas 2005). Second- or third-entry burns may then consume these woody fuel inputs from the first burn (Collins *et al.* 2018). Therefore, it may not be until the third-entry burn that prescribed fires begin to have a durable effect on the fuel load.

It is thereby important that analyses of fuel consumption in prescribed burns in California consider both first-entry and multiple repeat-entry burns. A comprehensive exploration of the plot and stand-level predictors of fuel consumption could aid managers in accounting for high levels of variability in fuel consumption. Management informed by such an analysis could additionally improve burn efficacy for a variety of potential management objectives. Furthermore, agencies that regulate air quality may benefit from improved understanding of fuel consumption in initial entry *v.* repeat burns.

The longitudinal study implemented at Blodgett Forest Research Station as part of the national Fire and Fire Surrogate Study provides a valuable opportunity to improve our understanding of fuel consumption across repeated burns by measuring fuel consumption for first-entry, second-entry and third-entry prescribed burns (Fig. 1) (Weatherspoon and Skinner 2002). Our specific research questions were the following. (1) How does fuel consumption differ between first- and repeat-entry prescribed burns in a fire-excluded Sierra Nevada mixed-conifer forest? (2) Which measurable characteristics affect fuel consumption and how may that vary by burn number and stand? (3) Can these characteristics be used to predict fuel consumption?

Methods

Study location

Data for the present study were collected at Blodgett Forest Research Station, a University of California-owned research forest located on the western slope of the Sierra Nevada Mountains in El Dorado County, California (38°52′N, 120°40′W; Fig. 2). The forest is located between 1200 and 1500 m in elevation and exhibits characteristics typical of high productivity Sierra Nevada mixed-conifer forests that experienced multiple timber harvests and fire suppression/exclusion. The overstorey is primarily composed of five conifer species: sugar pine (*Pinus lambertiana*, 14.2% of total plot basal area); ponderosa pine (*Pinus ponderosa*, 15.5%); white fir (*Abies concolor*, 22.0%); Douglas-fir (*Pseudotsuga menziesii*, 18.7%); and incense-cedar (*Calocedrus decurrens*, 19.8%). California black oak (*Quercus kelloggii*, 8.1%) is present but comprises a less-significant portion of the overstorey than the five conifer species.

The climate at Blodgett is mediterranean. The largest portion of annual precipitation (averaging 151 cm during the study period from 2001 to 2017) falls during winter and spring (November-April) with less than 1/3 of total precipitation as snow (R. York, unpubl. data). The region experiences yearly drought beginning in late spring or summer and extending into autumn. Winters are cool, with average January temperatures of 5°C, while August averaged 21°C from 2001 to 2017.

In the period before Anglo-European settlement, Blodgett Forest experienced frequent low–mixed-severity fires with an average fire-return interval between 9 and 15 years (Stephens and Collins 2004). Since the early 1900s, Blodgett's disturbance history was characterised primarily by an extended period of fire exclusion. Initial harvest of the site occurred in the early 20th Century (Olson and Helms 1996). After initial harvest, stands at Blodgett Forest developed from natural regeneration without manipulations. The forest has been actively managed via a combination of even and uneven-aged silvicultural methods and active fire suppression since 1933.

Treatment structure and schedule

The experimental portion of the present study was conducted as part of the larger Fire and Fire Surrogate Study (McIver *et al.* 2009). As a part of that study, 12 individual stands ranging in size from 14 to 29 ha, were selected and randomly assigned one of four treatments: control; prescribed fire only; mechanical thin; or mechanical thin followed by prescribed burn. The present study focuses on data from just one of the treatments, 'prescribed fire only', which was implemented in three different stands enumerated 60, 340 and 400. Fall burns were conducted in each of these stands in 2001, 2009 and 2017 (specific dates are reported in Table 1) using strip head fires. Fuel moisture and weather conditions were consistent with those commonly used throughout the region (Table 1).

Data

In each stand, a grid of 200.04-ha circular plots was installed using permanent markers at each plot centre and tree tags to ensure re-measurement of the same sample area. This grid was located in the internal 10 ha of each compartment so as to reduce the potential for adjacent compartment characteristics to influence measurements. Overstorey trees, ground fuels, surface fuels, shrub cover and snags were measured at each plot. Tree and snag measurements were taken during the summer preceding each burn. Species and diameter at breast height (DBH)

Fig. 1. Photographs taken before and after each prescribed burn in the present study. All photographs were taken from the same spot in Stand 400.

were recorded for every live tree >11.4-cm DBH in the 0.04-ha circular plots.

Shrub cover was estimated visually at each plot. In the first year of measurements, shrub cover of each species was estimated to be in one of four categories: 0%; 0–5%; 5–25%; or 25–100%. In subsequent measurements, shrub cover was estimated to the nearest 5%. To prevent precision discrepancies in the analysis, the more precise measurements were reassigned values from the four categories used during the first round of sampling.

Surface and ground fuels were sampled before and after each burn using the line-intercept method (Brown 1974). During the first sampling event, two transects were established at random azimuths from the plot centre. Repeat fuels measurements were taken on the same azimuths. Fuels were sampled as follows: 1-h (0–0.64 cm) and 10-h (0.64–2.54 cm) fuels were sampled between 0 and 2 m; 100-h (2.54–7.62 cm) between 0 and 3 m; and 1000-h (>7.62 cm) between 0 and 11.3 m. Duff, litter and total fuel depths (cm) were measured at two locations per transect. Fuel loads were calculated using appropriate species-specific coefficients developed for Sierra Nevada forests (van Wagtendonk 1996; van Wagtendonk *et al.* 1998). The coefficients used to calculate fuel loads were weighted using basal area fractions for each species in order to produce precise estimates of fuel load (Stephens 2001). Fuel consumption was then calculated for total ground fuels and for each fuel class according to the following equation: (fuel $\text{load}_{\text{pre-burn}}$ – fuel $\text{load}_{\text{post-burn}}$)/fuel $\text{load}_{\text{pre-burn}}$ (Fig. 3). Consumption was calculated as a proportion in order to normalise by pre-burn fuel loads. That way, the effects of burn number and fuel load on consumption could be parsed from the intrinsic effect of pre-burn fuel load on the magnitude of consumption.

Pre-burn fuel measurements were completed in August 2001 for the first burn, June 2009 for the second and August 2016 for the third. Post-burn fuel measurements were completed in February 2003 for the first burn, October 2009 for the second and November 2017 for the third. Freshly deposited litter and woody fuels laying on top of burnt material were treated as

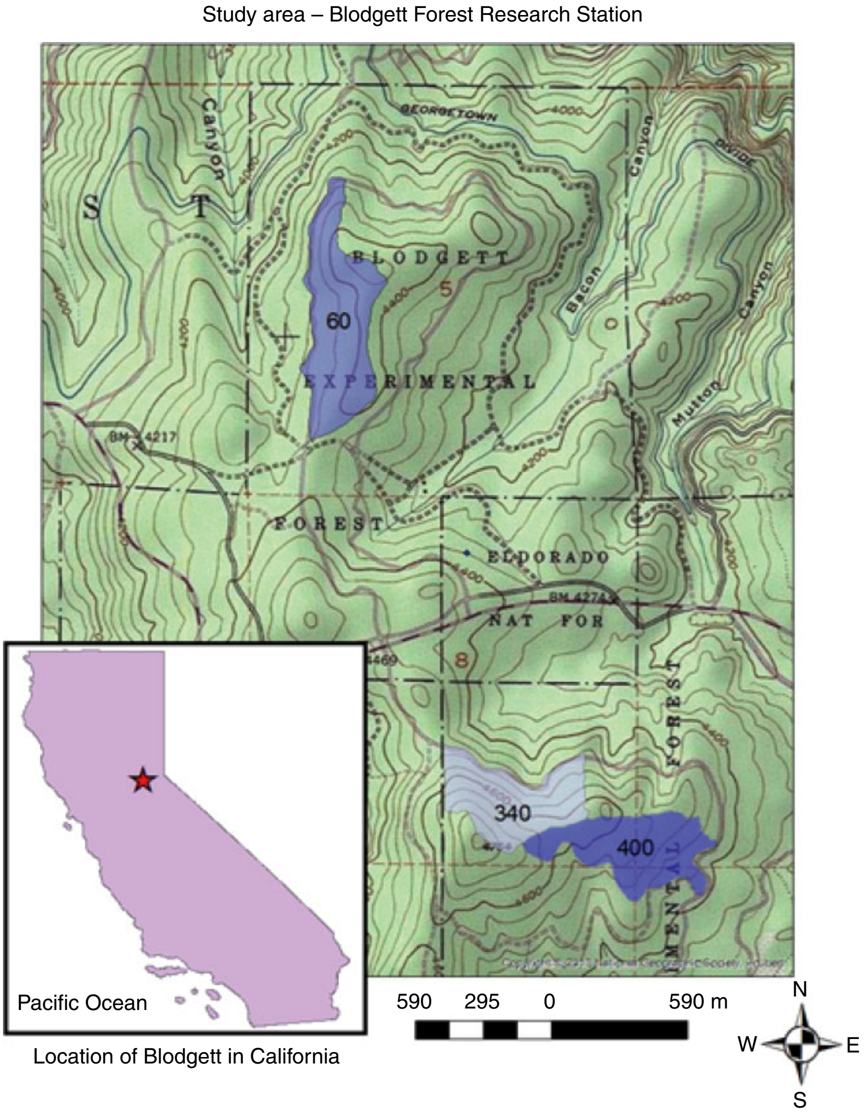

Fig. 2. Prescribed-fire-only stands of the Fire and Fire Surrogate Study at Blodgett Forest Research Station, Georgetown, California, USA.

Table 1. Prescribed-burn weather conditions

Blodgett Forest weather station data for the periods during which each prescribed-burn treatment occurred. All data are from the onsite Blodgett Forest weather station except fuel moisture, which is from the nearby Bald Mountain and Hell Hole Remote Automated Weather Stations

Burn number	Date	Temperature (°C)	Relative humidity (%)	Wind speed (km h^{-1})	10-h fuel moisture (%)
Burn 1	23 Oct–6 Nov 2002	8	35	0–7	7–10
Burn 2	8 Oct–10 Oct 2009	10	48	0	5–6
Burn 3	30 Oct–1 Nov 2017	17	35–45	1–2	5–7

post-burn fuel deposition and therefore not measured. However, in patches that did not burn during treatment it was impossible to separate pre-treatment fuels from post-treatment fuel deposition. This, along with other sources of measurement error when estimating fuel loads from line-intercept data, resulted in several instances in which total consumption was negative (i.e. post-burn fuel load exceeded the pre-burn fuel load). These instances were treated as no-burn situations, and total consumption was truncated at zero to avoid obvious errors in model fitting. Errors of this nature occurred in 19 out of 126 total observations.

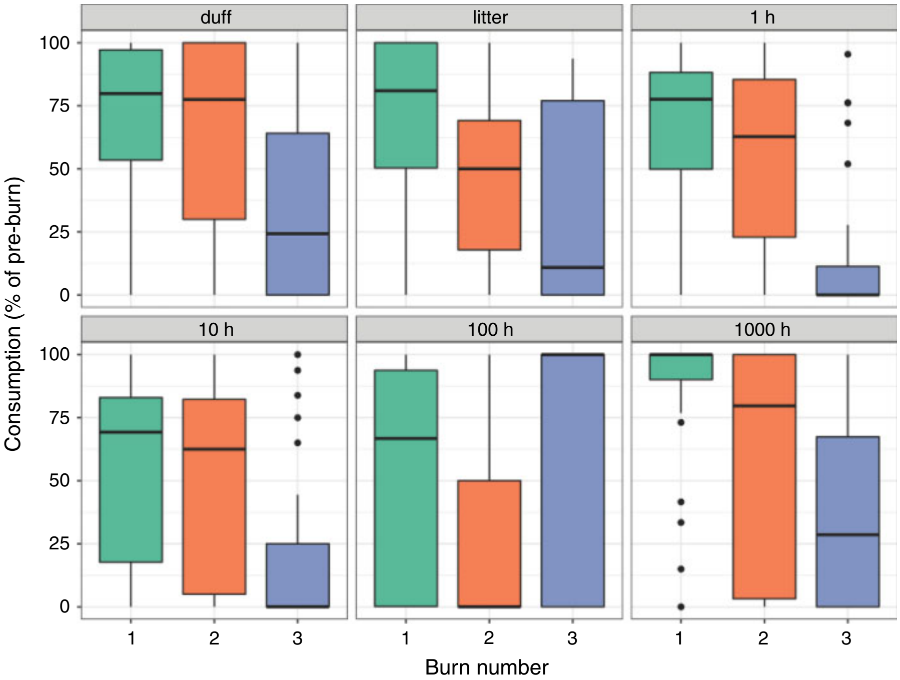

Fig. 3. Surface fuels consumption detailed by fuel class and burn number, summarised by stand. The mean observation, quartiles and outliers are represented by the thick line in the centre of each box, the ends of each box, the lines protruding from each box and the single points.

Aspect was directly measured at the sub-cardinal level (N, NW, W, etc.) at each plot and then converted to a measure of 'northness' for modelling purposes. To create this measure, the aspect N was treated as 1, S was treated as −1, E and W were 0, NW and NE 0.5, and SE and SW −0.5. Slope was measured to the nearest percentage in each plot.

Analysis

Stepwise model selection was utilised to determine the factors important in predicting consumption. The full model treats proportional consumption as a function of eleven fuel bed and stand characteristics. We considered the following model terms: species composition (expressed as basal area proportions of pine (ponderosa or sugar pine), fir (Douglas-fir or white fir) and incense-cedar); basal area of snags; basal area of live trees; percentage canopy cover; percentage cover of deer brush (*Ceanothus integerrimus*); pre-burn total fuel load; burn number; slope; aspect; and stand. These terms were hypothesised to influence fuel consumption on the basis of both prior research and *a priori* reasoning about their relationships to fire behaviour and fuel consumption (Lydersen *et al.* 2015).

We hypothesised that species composition would affect fuel consumption because of the divergent needle morphologies of the mixed-conifer species (Fonda *et al.* 1998; Fonda 2001). Therefore, species composition was considered according to broad categories of branch and needle morphology (pine, fir and incense-cedar) (Lydersen *et al.* 2015). In order to meet the assumptions requisite for linear mixed-effects modelling, total fuel load was log-transformed. Stand is included as a fixed effect in order to both reflect the nested structure of the experimental design, and to capture the importance of unmeasured, structural differences between stands such as weather patterns and stand histories. Deer brush was the only shrub considered in the model because it was the only species with consistent representation in all three burn entries and stands. It is also the dominant shrub species across Blodgett Forest and has been observed to influence fire behaviour during prescribed burning.

We also considered interactions between species composition and burn number because of the suspicion that the fuel structure present in the first burn, created though a century of fuel accumulation, would prevent the expression of any of the subtle effects related to differential needle morphology outlined previously. Considering interactions between species composition and burn number prevents the special conditions present in Burn 1 from obscuring the effect of species composition in Burns 2 and 3.

Models were constructed as linear mixed effect models, with random effects specified at the plot level. Models were fit using the package nlme (Pinheiro *et al.* 2018) in the statistical analysis program *R* (R Core Team 2018). All continuous explanatory variables were normalised to zero mean and unit standard deviation in order to improve model fit and facilitate effect-size comparisons. The means and standard deviations of each included variable are listed in the results section for reference. Stepwise model selection was performed using likelihood ratio tests starting with a full model (all fixed effects included). The model term with the highest *P*-value according to the model summary output at each step was selected to be left out in the subsequent step. A likelihood ratio test was then performed in *R* to determine if the reduced model was a significantly worse fit. If the reduced model was not significantly different, it was kept

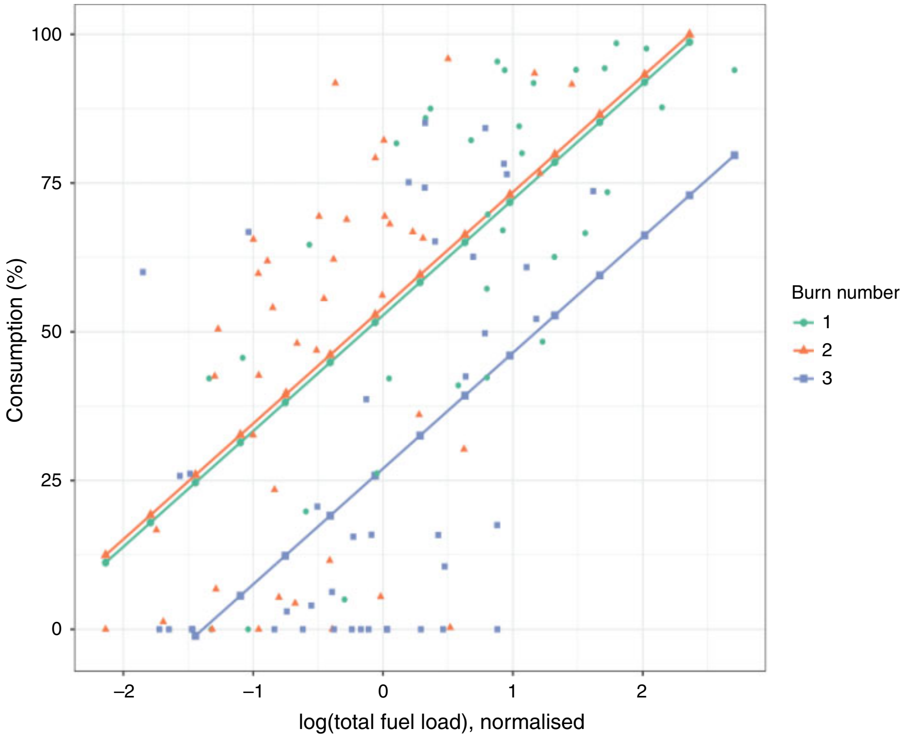

Fig. 4. Predicted surface fuel consumption as a function of both normalised log(fuel load) (mean = 3.92, s.d. = 0.64) and burn number displayed over observed data. Different prediction lines are shown for each burn number; observations and lines are coloured by burn number ($R^2 = 0.671$).

and a new model term was chosen to leave out using the same method. A final model was determined once no terms could be removed without resulting in a model of significantly worse fit. This methodology is outlined in greater detail in Zuur *et al.* (2009). For the purposes of model selection, parameters were estimated using the maximum likelihood (ML) method. Once a model was selected, the parameters were re-estimated using restricted maximum likelihood. A Shapiro–Wilk normality test was used to validate assumptions after the best-fitting model had been selected.

Model predictions were generated in *R* over a simulated dataset of regularly spaced values representative of the full ranges of each variable present in the original dataset. These predictions were then plotted over the original data to demonstrate model fit (Figs 4, 5). A post hoc analysis was then employed to examine specific differences in consumption between each burn within the context of the model. To do so, pairwise comparisons were constructed and analysed using two-way Tukey tests (Tukey 1949), using an α-level of 0.05 to infer statistical significance. We also tested differences in the main effects of stands in order to further explore the nature of stand-level variability in fuel consumption. Tests were implemented using the package multcomp (Hothorn *et al.* 2008) in *R*.

Results

Consumption averaged 45% across all stands and burns. In general, fuel consumption was highest in the first burn, and in the duff and 1000-h fuel classes across burns (Table 2, Fig. 3). A considerable amount of variability was observed in consumption between fuel classes, burn number and among stands (Table 2, Fig. 3). The highest variability was observed in the 100- and 1000-h fuel classes, although differences in variability between fuel classes were less pronounced than differences in consumption. The magnitude of variation was similar across both stands and burn number.

Model selection indicates that the best-fitting model includes total fuel load (mean: 3.92, sd: 0.64), percentage basal area pine (mean: 0.21, sd: 0.23), slope gradient (mean: 19.72, sd: 7.92), canopy cover (mean: 65.12, sd: 14.78), live tree basal area (mean: 49.35, sd: 16.48), burn number and stand as fixed effects, with an interaction between percentage basal area pine and burn number ($R^2 = 0.671$, Table 3). Notably, the model selected using stepwise likelihood ratio tests was also the Akaike Information Criterion (AIC) minimising model (AIC = 1076.4). The two next-best-fitting models included aspect and percentage cover of deer brush and had AIC scores of 1078.3 and 1080.3. A Shapiro–Wilk normality test ($W = 0.993$, P-value = 0.807) indicated that model residuals were normally distributed.

Fitted model terms indicated a strong, positive relationship between fuel load and consumption (Table 3). The main effect of percentage basal area of pine species on consumption for the first burn was negative, while for Burns 2 and 3 it was strongly positive. Additionally, the modelled main effects of both Burn 2 and Burn 3 on consumption was negative, meaning that consumption in these burns was lower than consumption in Burn 1. The stand and fuel-bed characteristics included in the

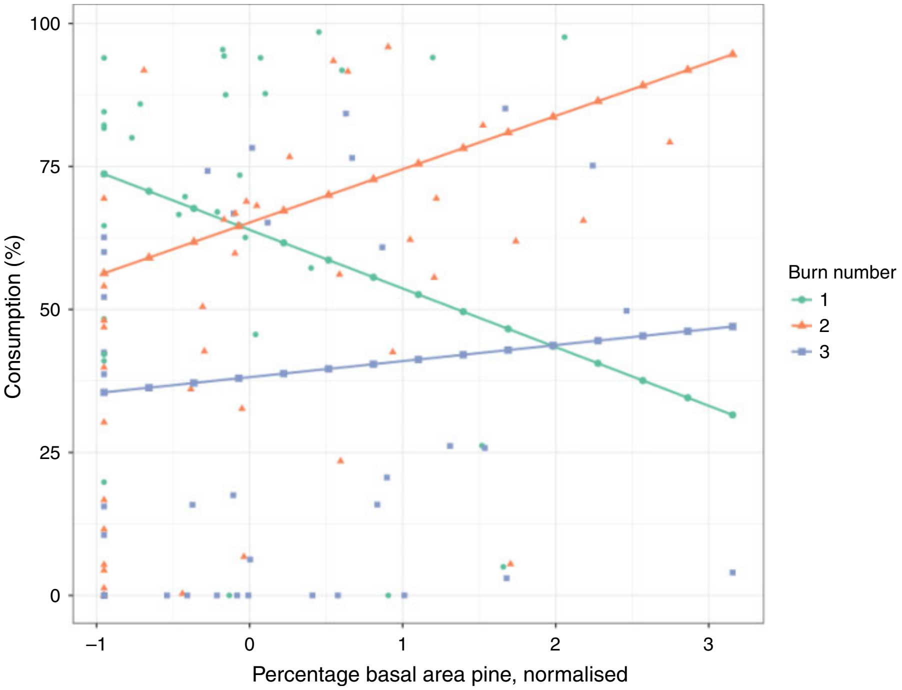

Fig. 5. Predicted surface fuels consumption as a function of both normalised percentage basal area of pine (mean = 21.9%, s.d. = 23.1%) and burn number displayed over observed data ($R^2 = 0.671$).

Table 2. Total fuel consumption by burn number and fuel class

Mean surface fuels (Mg (Megagrams) per hectare) consumption and standard deviations categorised by fuel class and burn number, totalled across stands. Average column displays average consumption across both burns and stands. Pre-burn fuel loads are provided for context. Note: values are averaged across units and plots

Fuel class	Average			Burn 1			Burn 2			Burn 3		
	Pre-burn fuel load (Mg ha^{-1})	Consumption (%)		Pre-burn fuel load (Mg ha^{-1})	Consumption (%)		Pre-burn fuel load (Mg ha^{-1})	Consumption (%)		Pre-burn fuel load (Mg ha^{-1})	Consumption (%)	
		Mean	s.d.		Mean	s.d.		Mean	s.d.		Mean	s.d.
Duff	17.6	53	39	17.5	64	37	16.6	64	40	18.7	35	36
Litter	22.8	46	37	41.8	65	34	10.0	46	32	16.5	32	37
1 h	0.8	43	37	1.1	68	27	0.8	54	34	0.5	12	24
10 h	2.9	40	37	3.9	53	37	2.4	52	36	2.5	17	29
100 h	3.5	48	44	6.2	50	41	2.1	28	42	2.2	62	45
1000 h	16.5	60	42	22.8	85	27	12.0	58	44	14.7	37	37
Total	64.2	45	34	93.4	64	30	43.8	45	31	55.3	29	31

best-fitting model were percentage basal area of pine, slope gradient, canopy cover and basal area of live trees.

Plots of model predictions revealed high variability in the data around the predicted fits, while still demonstrating the strong positive relationship between fuel load and consumption. Differences in the main effects of stand and burn number were clearly visualised as the difference in prediction curve intercepts (Figs 4, 5). Differences in the slope gradient and intercepts of the prediction curves demonstrate the differences in interaction effects between pine composition and burn number (Fig. 4).

The two-way Tukey test on burn number revealed significant differences between the main effects of Burns 3 and 1 (difference = −25.8; P = 1.7e-05) and Burns 3 and 2 (difference = −27.0; P <1e-05), but no significant differences between Burns 2 and 1 (difference = 1.3, P = 0.973). The Tukey test on stand demonstrated significant but variable differences in the effects of stand on fuel consumption, indicating substantial stand-to-stand heterogeneity not explained by the other variables in the model. Specifically, the stand that exhibited the highest overall consumption in all three burns (Stand 400), had a main effect that was significantly greater (difference = 36.79; P = 0.001) than the main effect of the stand with the lowest overall consumption (Stand 340). There were no other significant differences between the effects of stands.

Table 3. Best-fitting model parameter estimates

Model term coefficient estimates and standard errors for the best-fitting model of surface fuel consumption from a prescribed-fire treatment. Parameters estimated using restricted maximum likelihood. Continuous data were normalized prior to model fitting, means and sds of each continuous explanatory variable are listed in the results section

Parameter	Estimate	s.e.
Intercept	52.8	6.2
Log (fuel load)	19.5	2.4
Slope gradient	9.2	3.9
Live tree basal area	7.7	3.4
Canopy	−5.5	3.0
Unit 340	−15.7	9.4
Unit 400	11.1	6.1
% Pine	−10.3	5.0
Burn 2	1.3	5.7
Burn 3	−25.8	5.7
% Pine: Burn 2	19.6	5.6
% Pine: Burn 3	13.1	5.5

Discussion

In the present study, we detail and identify several important drivers of fuel consumption for a replicated study of repeated prescribed fire in a mixed-conifer forest. Model selection points to four primary drivers of fuel consumption: fuel load; basal area of pine species; burn number (first, second or third entry); and individual stand. Informatively, five of the seven factors included in the best-fitting consumption model were directly measured stand characteristics: pre-burn fuel load; percentage basal area of pine; slope gradient; canopy cover; and basal area of live trees. The other two, burn number and stand, were more nuanced, likely representing the influence of several unmeasured characteristics in addition to their primary, mechanistic effects. Despite this complexity, our analysis revealed several important insights about fuel consumption patterns in Sierra Nevada mixed-conifer forests.

One insight is that the strong relationship between fuel load (log-transformed) and consumption indicates the importance of fuel availability in burn efficacy. The magnitude and direction of this effect indicates that as the total fuel load increases, the proportion of the fuel bed consumed also increases. It follows that the relationship between fuel load (untransformed) and consumption is exponential. There are two primary interpretations of this shape, which are not mutually exclusive. The first suggests that greater fuel availability affects fire behaviour by either increasing fire intensity (in the case of high pre-burn fuel loads from large fuel classes) and/or by increasing residence time (in the case of high duff and litter loads) (Albini 1978).

The second possible explanation for the shape of this relationship is that high overall pre-burn fuel loads may be associated with more homogeneous fuel conditions throughout the study stands. Not surprisingly, the highest pre-burn fuel loads were observed before Burn 1 (Table 2), which occurred nearly 100 years after the last fire recorded in the tree ring record (Stephens and Collins 2004). This fire-free period allowed for considerable dead fuel accumulation in both the vertical and horizontal orientations (Stephens and Moghaddas 2005). This accumulation, which has been observed in other productive mixed conifer forests (e.g. Knapp *et al.* 2005; Lydersen *et al.* 2015) also tends to lead to greater fuel continuity throughout forest stands (Miller and Urban 2000), which can allow for uninhibited fire spread and ultimately more complete fuel consumption.

The model indicates that there is an effect of burn number on consumption beyond what can be explained by differences in pre-burn fuel loads. According to the two-way Tukey test, Burn 3 is significantly different from each other burn ($P < 0.05$). The differences between parameter estimates suggest that even after controlling for differences in pre-burn fuel load, Burns 1 and 2 experienced the highest consumption while Burn 3 experienced significantly lower consumption. Previous studies have suggested that because of a fuel pulse created by high mortality in small- and medium-size tree classes during a first-entry burn, a restored fuel bed condition may not be reached until after the second-entry burn (Collins *et al.* 2018). Thereby, Burn 3 would be the first burn acting as a 'maintenance burn'. This explanation accounts for the observed differences in consumption between the first two burns and Burn 3. However, in this case there was little evidence for an added fuel pulse following the first burn. In fact, Burn 2 experienced the lowest average pre-burn fuel loads of all burns (Table 2).

Another possible explanation for the differences in the effect of burn number on consumption is that each burn increases overall fuel discontinuity, thereby reducing consumption in each subsequent burn regardless of pre-burn fuel load. This mechanistic explanation is supported by previous studies that suggest that prescribed burns decrease fuel continuity, which results in more variable severity and consumption (Knapp and Keeley 2006; Lydersen *et al.* 2014). However, this does not explain the similarity in consumption between Burns 1 and 2.

A limitation of the present study is that burn replicates occurred in the same years. Therefore, we cannot statistically separate the effect of year (or climate) from the effect of burn number. However, data from other studies provide further evidence that the differing effects of each burn are a result of mechanistic differences rather than year-to-year variation. A review of published consumption from 17 first-entry burns conducted in a diverse range of California forests and during a time frame spanning more than two decades provides an estimate of the range of year-to-year variation in consumption for first-year burns. Using data from Kauffman and Martin (1988), Knapp *et al.* (2005), and Vaillant *et al.* (2009) we determine the mean consumption of the surveyed first-entry prescribed burns to be 63.5% with a standard deviation of 19.7%. This places the consumption of Burn 2 (45%) ~1 standard deviation below the average, and Burn 3 (29%) about two standard deviations below the average.

The observed effect of the composition of overstorey pine species is interesting for several reasons. We originally hypothesised that the needle morphology of pine species would result in increased consumption as a result of the lower bulk densities observed in litter beds composed primarily of pine needles (van Wagtendonk *et al.* 1998). We additionally hypothesised that this effect would be negated in the first burn because of a possible fuel 'saturation' effect driven by long period without fire (Lydersen *et al.* 2015). The coefficients which we fit for the best-fitting model appear to validate this hypothesis. In Burns 2 and 3, there was a strong, positive relationship between percentage pine and fuel consumption, yet this effect was negative in Burn 1. A possible explanation of these contrasting effects is that consumption in Burn 1 may have been more tied to fine woody accumulation, which tends to be greater in areas with higher proportions of white fir (Lydersen *et al.* 2015; Fry *et al.* 2018) and thus lower pine proportion. As a result of the relatively high fuel consumption overall in Burn 1, it is likely that the high litter deposition rates of ponderosa pine relative to the other mixed conifer tree species (van Wagtendonk and Moore 2010) was a dominant driver of fuel consumption in subsequent burns (recall that Burns 2 and 3 were 7 and 15 years after Burn 1). These results indicate that managing stands for increased pine composition could result in more effective prescribed-fire implementation in a repeat-burn scenario. Increased pine proportion is consistent with historical forest conditions in these forests (Knapp *et al.* 2013; Stephens *et al.* 2015; Collins *et al.* 2017) and is often a stated restoration goal for mixed conifer forests (North 2012).

The best-fitting model additionally indicates a negative effect of canopy cover on consumption. This effect is intuitive given that as canopy cover increases, solar radiation on the fuel bed decreases. This in turn results in lower temperature and higher relative humidity and fuel moisture, especially in periods immediately after rain. The model also indicates a positive effect of basal area of live trees on fuel consumption. One possible explanation for the opposing signs of the two effects has to do with the influence of forest structure on microclimate. Take for example stands with high canopy cover, but low basal area. We can infer that these stands are likely composed of many small trees. Conversely, stands with high canopy cover and high basal area are likely composed of fewer, larger trees. The data in our study support these assumptions. Stands in the 70th percentile or higher for canopy cover but the 30th percentile or lower for live tree basal area had on average 905 trees per hectare with a quadratic mean diameter of 38.7 cm. Conversely, stands in the 70th percentile or above in basal area but the 30th or below in canopy had on average only 234 trees per hectare with a quadratic mean diameter of 61.4 cm. The stands with many small trees likely have a more closed structure, whereas the stands with larger trees likely have a more open structure. Stands with more closed structure experience higher relative humidity, lower temperature and therefore higher fuel moisture than the open stand, which could result in lower consumption, hence the positive effect of basal area (Rambo and North 2009; Ma *et al.* 2010). Another possible explanation is that higher fuel production, which can be positively related to basal area (van Wagtendonk and Moore 2010), partially offsets the effect of repeat prescribed burns on fuel continuity. In addition to depositing more fuel, large trees with larger canopy radii and higher crowns likely deposit fine fuels more uniformly at the plot scale than small trees.

It should be noted that basal area of live trees and canopy cover are collinear in this case ($r = 0.5$). In many cases, collinearity can cause issues in parameter estimation (Zuur *et al.* 2010). However, the variance inflation factors (1.9 for canopy and 2.2 for basal area) indicate that the issue is not severe and interpretation of the slope gradient estimates is valid. For reference, Zuur *et al.* (2010) identified a variance inflation factor of 3 as a stringent threshold for collinearity problems.

In general, we observed high levels of variability in consumption between stands. Additionally, the two-way Tukey test on stand indicates the existence of significant stand-to-stand variability in consumption beyond what can be explained by the other independent variables included in the model. This finding agrees both with qualitative descriptions of prescribed burns given by managers and previous fuel consumption analyses of fire-excluded forests that were historically adapted to frequent fire (Kauffman and Martin 1988; Hille and Stephens 2005; Knapp *et al.* 2005; Nesmith *et al.* 2011).

Variability in prescribed-fire fuel consumption points to an inherent challenge in burn implementation. Even the most well planned burns under ideal conditions can experience high amounts of irregularity in consumption, which can lead to variable efficacy depending on burn objectives. Much of this stand-to-stand variability is likely a result of variation in unmeasured stand-level characteristics ranging from microclimate to fire ignition strategies (e.g. the space between adjacent strip head fires). Future studies should seek to better quantify and explore stand-level differences in both environmental and fire-behaviour-related characteristics in order to improve our ability to model and predict fuel consumption.

Despite these unmeasured sources of variability, the model developed in the present study explains ~67% of the variation in plot-level consumption. This result still supports the ability of our model to identify the factors important in driving fuel consumption. Furthermore, in many cases variability in forest structural characteristics is a stated objective of prescribed-fire management (Knapp and Keeley 2006; North *et al.* 2009). Prescribed burns with variable consumption likely better approximate the function of historical fires in the Sierra Nevada, which occurred under conditions of reduced and less continuous fuel loads (Knapp and Keeley 2006). The heterogeneous structure created by variable, repeat burns is beneficial from an ecological standpoint, possibly increasing forest resilience and fostering diversity in both structure and composition (North *et al.* 2009). Additionally, variability in consumption could allow for spatial refugia, promoting tree recruitment and providing relief for some animal species (Knapp and Keeley 2006).

Many of the aforementioned sources of variation are spatial in nature and therefore captured by either the fixed effect of stand or random plot effects. Locational consumption differences are likely affected primarily by topography. Aspect and slope gradient both affect the amount of solar radiation experienced at a given location. In the Sierra Nevada, south facing, steep slopes experience the greatest amounts of solar radiation. The effect of Stand 400 on consumption was significantly higher than the effect of Stand 340 ($P < 0.05$) according to the two-way Tukey test. Stand 400 faces generally south-east, while Stand 340 faces generally north. This trend is also clear at the plot level. Plots with north-western, north-eastern and northern aspects experienced an average consumption of 37.5%, whereas plots with southern, south-eastern and south-western aspects experienced an average consumption of 54.6%. Model selection did not indicate the utility of the inclusion of aspect in the best-fitting model. However, this could be an artefact of its collinearity with stand.

The best-fitting model does indicate a positive effect of slope gradient on fuel consumption. This effect is well studied, and often included in predictive models of fire behaviour (Albini 1978; Dupuy 1995). As slope gradient increases, the ability of a fire burning upslope to ignite and consume materials increases (Dupuy 1995). It is likely through this mechanism and the result of this on solar radiation that slope gradient affects fuel consumption in our study.

One limitation of the present study is that fuel moisture was not measured on each plot. Previous studies have established the importance of fuel moisture in determining fuel consumption in Sierra Nevada mixed-conifer forests (Kauffman and Martin 1988). Still, while they are not directly measured, fuel moisture effects are likely wrapped up in the modelled effects of burn number, stand and plot. Fuel moisture is shown to vary between locations and from year to year depending on climate patterns. However, Table 1 demonstrates minimal variation in fuel moisture between the burns in the present study. Furthermore, it is illustrative that burn number by stand interactions were not included in the best-fitting model. This result indicates that the effects of unmeasured variation at the individual burn level (each stand and year combination), including that of fuel moisture, are not significant. It additionally provides support for a mechanistic interpretation of the effects of burn number and stand.

A second limitation of the present study involves the sampling methodology. Fuel beds are notably complex, and accurate estimates of fuel loads are difficult to obtain without intensive sampling efforts (Keane 2013). The present study employed Brown's planar intersect method for fuel bed sampling (Brown 1971). Although often shown to outperform many of the other commonly applied fuel sampling techniques, Brown's method has significant limitations, especially when employed at small total sampling lengths (Sikkink and Keane 2008; Keane 2013; Keane and Gray 2013). The primary concern with Brown's method is that small transects may not capture the full range of within-plot variability in fuel loads, leading to inaccurate or biased estimates of plot-level fuel loads. It is certain that the accuracy of plot-level fuel load estimates in this study would have been improved by using longer or more numerous transects. However, the sampling design employed in the study significantly reduces the risk of systematic bias. Namely, initial randomisation of transect azimuth as well as the use of multiple transects per plot reduces bias relating to fuel particle orientation and patchiness in fuel load distribution. Furthermore, by maintaining consistent transect azimuths through time we ensure that differences between pre- and post-fire fuel measurements are the result of fuel consumption in the prescribed fire and not locational differences in fuel load. In general, although we recognise the shortcomings of the planar intersect method for describing variable and patchy forest fuel loads, we maintain that given the efforts to control for systematic bias, these shortcomings are not problematic enough to cast doubt on the outcomes of this study.

Conclusion

Fuel consumption, which is a product of pre-burn fuel load, weather and local fire behaviour, is inherently variable. However, understanding the mechanisms behind fuel consumption patterns is of urgent interest to managers and policymakers seeking to combat increased fire hazard in California's Sierra Nevada conifer forests (Little Hoover Commission 2018). By developing a predictive model, the present study provides novel and valuable insights into the drivers of fuel consumption in repeat prescribed burns, which can aid managers seeking to achieve particular objectives related to prescribed fire, policymakers hoping to design effective restoration or risk-mitigation legislation, and regulators interested in predicting prescribed-fire emissions.

The present study reveals high levels of variability in fuel consumption even within stands and burn numbers. In many cases, this heterogeneity is desirable to managers owing to its potential to increase forest resilience and diversify forest structures. Additionally, despite the predictive challenge posed by the variable character of prescribed-burn fuel consumption, our model explains ~67% of the plot-level consumption variability. Results furthermore indicate the importance of fuel load, slope gradient, canopy cover, basal area of live trees, stand, burn number and species composition in determining fuel consumption. Specifically, we conclude that managing for increased pine composition could aid managers in increasing fuel consumption in repeat prescribed burns.

Conflicts of interest

The authors declare no conflicts of interest.

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