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Simulated fire behaviour in young, postfire lodgepole pine forests

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Abstract. Early-seral forests are expanding throughout western North America as fire frequency and annual area burned increase, yet fire behaviour in young postfire forests is poorly understood. We simulated fire behaviour in 24-year-old lodgepole pine (*Pinus contorta* var. latifolia) stands in Yellowstone National Park, Wyoming, United States using operational models parameterised with empirical fuel characteristics, 50–99% fuel moisture conditions, and 1–60 km hr^{-1} open winds to address two questions: [1] How does fireline intensity, and crown fire initiation and spread vary among young, lodgepole pine stands? [2] What are the contributions of fuels, moisture and wind on fire behaviour? Sensitivity analysis indicated the greatest contributors to output variance were stand structure mediated wind attenuation, shrub fuel loads and 1000-h fuel moisture for fireline intensity; crown base height for crown fire initiation; and crown bulk density and 1-h fuel moisture for crown fire spread. Simulation results predicted crown fire (e.g. passive, conditional or active types) in over 90% of stands at 50th percentile moisture conditions and wind speeds greater than 3 km hr^{-1}. We conclude that dense canopy characteristics heighten crown fire potential in young, postfire lodgepole pine forests even under less than extreme wind and fuel moisture conditions.

Additional keywords: ecological memory, fire ecology, fuel dynamics, *Pinus contorta*, Rocky Mountains, subalpine forest, succession, Yellowstone National Park, young forests.

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Introduction

Shifting patterns in global temperature and precipitation have been observed over the past three decades, and are projected to accelerate over the next century, leading to increases in the frequency and extent of wildland fire (Flannigan *et al.* 2000, 2009; Scholze *et al.* 2006; Westerling *et al.* 2006; Moritz *et al.* 2012; Westerling 2016; Abatzoglou and Williams 2016). In subalpine forest ecosystems prone to stand-replacing fire, increased burned area will lead to the expansion of young, regenerating forest stands. Until recently, effects of postfire succession on subsequent fire behaviour have been poorly described. A growing body of evidence indicates that time-since-fire plays an important role in the self-regulation of fire, especially as fires overlap at shortened intervals (Peterson 2002; Collins *et al.* 2009; Price and Bradstock 2010; Teske *et al.* 2012; Collins *et al.* 2015; Parks *et al.* 2015; Coppoletta *et al.* 2016; Parks *et al.* 2016; Stevens-Rumann and Morgan 2016). To understand how young subalpine forests might burn in short-interval fire, we investigated the contributions of fuels, fuel moisture and wind on potential fire behaviour in 24-year-old lodgepole pine (*Pinus contorta* var. latifolia) forests that established after the 1988 fires in Yellowstone National Park (YNP).

Extensive stand-replacing fires (i.e. complete tree death) are common in subalpine lodgepole pine forests during periods of severe fire weather (Romme 1982; Lotan *et al.* 1985; Bessie and Johnson 1995; Schoennagel *et al.* 2004). Greater frequency and severity of drought over the next century are projected to reduce fire intervals and shift the forest mosaic towards a greater abundance of young forests (Schoennagel *et al.* 2006; Westerling *et al.* 2011). Stand replacing fires temporarily reduce fuel biomass and continuity, especially fine dead fuels and live canopy fuels (Kashian *et al.* 2006), and initiate a period of reduced burn probability as fuels reaccumulate. Such a negative feedback does not preclude fire from burning in young forests during extreme wind and drought, but does imply that fuel limitation may reduce fire extent and severity during the first decades following fire. In the northern Rocky Mountains, the likelihood of a second fire may be reduced up to 20 years (Parks *et al.* 2016) while burn severity may be reduced for 10–12 years (Harvey *et al.* 2016).

Historically, fires in YNP's young lodgepole pine stands rarely transitioned from surface-to-crown fire in the absence of high winds, and predominantly occurred when fire spread from adjacent mature stands under severe fire weather (Despain 1990; D Abendroth, A Norman, M Johnston, R Renkin, B Smith, pers. comm., 2015). Recent fires, including the 2012 Cygnet, 2010 Antelope and 2002 Phlox fires were consistent with these observations; however, fires in 2016 reburned over 18 000 ha of post-1988 forests, the greatest burned extent in YNP since 1988. We previously quantified fuel loads in post-1988, 24-year-old lodgepole pine stands and found fuels suitable for high-severity surface fires in 76% and crown-fire spread possible in 63% of our sample of the post-1988 Yellowstone landscape (Nelson *et al.* 2016). These estimates of fire potential were solely based on fuels thresholds (Reinhardt *et al.* 2006; Sikkink and Keane 2012) and did not incorporate the effects of wind, fuel moisture and detailed fuel characteristics represented in more sophisticated fire models. More rigorous fire behaviour analyses are needed to fully understand the controls exerted by weather and fuel conditions on surface and crown fire behaviour in young forests.

Our objective was to assess the variation and drivers of potential fire behaviour in young, post-1988 lodgepole pine stands burned under a range of fuel moisture and wind conditions using a comprehensive set of operational fire models. We simulated potential fire behaviour in 82 lodgepole pine stands that regenerated following the 1988 fires in YNP (Wyoming, United States (US)) to address two questions: [1] How does fireline intensity, and crown fire initiation and spread vary among young, lodgepole pine stands? [2] What are the relative contributions of fuel loads, fuel moisture and wind on simulated fire behaviour? YNP is the premiere landscape for such a study because human intervention on fire regimes and forest dynamics have been minimal, substantial reductions in future fire intervals have been projected (Schoennagel *et al.* 2006; Westerling *et al.* 2011) and the scale of the 1988 fires represents the anticipated magnitude of mega-disturbances under projected climate conditions (Running 2006).

Materials and methods

Study area

Yellowstone National Park is a mostly roadless landscape primarily managed as wilderness encompassing ~900 000 ha along the continental divide in north-western Wyoming, US. The park ranges from 2100 to 2700 m in elevation with ~80% of the landscape covered in forests. At the Old Faithful weather station, mean annual precipitation is 645 mm and mean annual temperature is 1.2°C, with winter lows averaging −17.6°C in January and summer highs averaging 23.8°C in July (1981–2010; http://www.wrcc.dri.edu; accessed 1 October 2016). Lodgepole pine is the dominant tree species, occurring primarily on infertile, rhyolitic substrates and slightly less infertile andesitic substrates (Turner *et al.* 2004). Engelmann spruce (*Picea engelmanii*) and subalpine fir (*Abies lasiocarpa*) can dominate on more fertile sites, and whitebark pine (*Pinus albicalus*) can be found in pure stands at high elevations.

In 1988, extensive fires burned across 45% of the subalpine plateau (Turner *et al.* 1994) resulting in the conversion of 170 000 ha of forest to early-seral lodgepole pine forests (Despain 1990; Kashian *et al.* 2004). Twenty-four years later, regenerating lodgepole pine trees varied in density from 0 to 344 000 stems per hectare (Turner *et al.* 2016) and produced a wide range of available canopy fuel loads [range: 0.0–46.6 Mg ha^{-1}] and canopy bulk densities [range: 0.0–2.3 kg m^{-3}], with canopy fuels in the densest stands exceeding those found in mature lodgepole pine forests (Nelson *et al.* 2016). Litter and 1-h fuels varied positively with post-1988 stem density and averaged 5.61 Mg ha^{-1} and 0.17 Mg ha^{-1}. Mean total surface fuel loads were 123 Mg ha^{-1}, with 1000-h fuels accounting for 88% of surface fuel loads. Surface fuels, in many stands, were in direct contact with canopy fuels.

Fire model formulation

Our objective was to simulate potential fire behaviour across the post-1988 Yellowstone landscape using empirical fuel characteristics, fuel moisture and wind conditions (Table 1). Fuel characteristics for each study site ($n = 82$) were input into a custom-built fire simulation system linking operational fire behaviour models to predict fireline intensity, and crown fire initiation and spread (Fig. 1, Table 1). This approach assumed that: [1] fuels are homogeneously distributed within each study site; [2] forest fires are capable of equilibrium conditions (i.e. we do not account for temporal variation in fire behaviour); [3] topographic effects on fuel moisture and wind are uniform across our study area; [4] empirically based sub-models provide reasonable estimates in our system (i.e. standard fire behaviour fuel models (FBFM) are suitable to estimate surface rate of spread (sROS) when fuel conditions are deemed reasonably similar to a standard FBFM); and [5] the sites sampled in this study reflect a random sample of the post-1988 forest conditions across YNP. Slope in our study sites ranged from 0 to 10 degrees and was set to zero in our modelling framework for ease of comparison.

Surface fireline intensity (I_b)

Surface fireline intensity (I_b; kW m^{-1}) was estimated using a derivation of Byram's (1959) fireline intensity equation (Eqn 1; Andrews and Rothermel 1982; Scott and Reinhardt 2001) where sROS is forward rate of fire spread (m min^{-1}) and HPA is heat release per unit area (kJ m^{-2}) in the flaming front.

$$I_b = sROS \times HPA \qquad (1)$$

sROS was estimated using a reduced set of standard FBFMs that best represent the empirical fuels data at each site and adjusted mid-flame windspeed (Andrews 2012). To assign standard FBFMs to each site, we: [1] applied a cluster analysis to our site-wise litter, 1-h, 10-h, 100-h, herbaceous and shrub fuel estimates using a k-medoid clustering algorithm; [2] estimated surface rate of spread (sROS) for each resulting fuels group using a custom FBFM; [3] selected the most similar FBFM from a subset of Scott and Burgan's (2005) FBFMs representing arid climate types (Rebain *et al.* 2010) by comparing custom model output with standard FBFM output using root mean square error (RSME) and mean bias in the Rothermel R-package (Vacchiano and Ascoli 2015); and [4] assigned the most similar standard

Table 1. Fire modelling input and output variables used to simulate potential fire behaviour in 24-year-old lodgepole pine (*Pinus contorta* var. latifolia) forests in Yellowstone National Park, WY, USA

Output variable	Abbr.	Input parameters (units)	References
Wind adjustment factor (fraction)	WAF	Canopy height (m) Canopy cover (fraction) Crown ratio (fraction) Fuel bed depth (m)	(Andrews 2012)
Surface rate of spread† ($m\,min^{-1}$)	sROS	Fuel loads ($Mg\,ha^{-1}$): duff, litter, 1-h, 10-h, 100-h, herb, shrub Wind: 6.1-m open wind speed ($km\,hr^{-1}$), WAF Fuel moisture (%; FMC): duff, 1-h, 10-h, 100-h, herbaceous, live woody (shrub)	(Rothermel 1972; Scott and Burgan 2005)
Heat per unit area‡ ($kJ\,m^{-2}$)	HPA	Fuel loads ($Mg\,ha^{-1}$): duff, litter, 1-h, 10-h, 100-h, 1000-h, herb, shrub Fuel moisture (%; FMC): duff, 100-h, 1000-h	(Albini and Reinhardt 1995, 1997; Reinhardt *et al.* 1997)
Fireline intensity (Eqn 1; $kW\,m^{-1}$)	I^b	Heat per unit area ($kJ\,m^{-2}$) Surface rate of spread ($m\,min^{-1}$)	(Byram 1959; Andrews and Rothermel 1982; Scott and Reinhardt 2001)
Critical crown initiation intensity (Eqn 2; $kW\,m^{-1}$)	I'	Crown base height (m) Fuel moisture (%; FMC): live foliar fuel moisture	(Van Wagner 1977; Cruz *et al.* 2004)
Crown fire rate of spread (Eqn 3; $m\,min^{-1}$)	cROS	Crown bulk density ($kg\,m^{-3}$) Fuel moisture (%; FMC): 1-h surface fuel moisture Wind: 10-m open wind speed ($km\,hr^{-1}$)	(Cruz *et al.* 2005; Alexander and Cruz 2006)
Criterion for active crown fire (Eqn 4; $m\,min^{-1}$)	CAC	Crown fire rate of spread ($m\,min^{-1}$) Crown bulk density ($kg\,m^{-3}$)	(Cruz *et al.* 2005; Alexander and Cruz 2006)

†As implemented in the Rothermel R package (Vacchiano and Ascoli 2015).
‡Estimated using 60 s median fire intensity in the First Order Fire Effects Model (FOFEM; Albini and Reinhardt 1995, 1997; Reinhardt *et al.* 1997; Sikkink and Keane 2012).

FBFM to each site according to its cluster group (Supplementary Figs. 1 and 2). Nineteen sites were assigned to the Low Load, Dry Climate Grass-Shrub (GS1) model representing sparse grass with small amounts of dead fuel particles with a RSME of 1.177, mean bias of −0.653, and mean cluster silhouette width of 0.18. Twenty-seven sites were assigned to the Moderate Dwarf Conifer with Understorey (TU4) representing short conifer trees with grass or moss understory with a RSME of 1.130, mean bias of 0.549 and mean cluster silhouette width of 0.23. Twenty-three sites were assigned to the Very High Load Broadleaf Litter (TL9) representing heavy broadleaf litter, or heavy needle drape, with a RSME of 0.217, mean bias of 0.115 and mean cluster silhouette width of 0.28

HPA was estimated using the first 60 s of combustion in the First Order Fire Effects Model (FOFEM). The Burnup model (Albini and Reinhardt 1995, 1997) used in FOFEM estimates fuel consumption and burn intensity using comprehensive empirical fuel profiles and fuel moisture conditions (Table 1).

Crown fire thresholds

Crown fire thresholds were estimated using Boolean logic. Crown fire initation was evaluated by computing a critical surface intensity threshold (Eqn 2; I'; kW m^{-1}) (Van Wagner 1977) where CBH is crown base height (m) and FMC is live foliar moisture content (%), then evaluating whether I_b exceeds I'. Crown fire rate of spread (cROS) was estimated using an empirical relationship developed in North American conifer forests (Eqn 3) where U_{10} is 10-m open wind speed (km hr^{-1}), CBD is crown bulk density (kg m^{-3}), and $FMC_{1\text{-h}}$ is 1-h fuel moisture content (FMC) (Cruz *et al.* 2005; Alexander and Cruz 2006). U_{10} was estimated by multiplying 6.1-m open wind speeds by 115% (Turner and Lawson 1978). Crown-to-crown fire spread was estimated using the criterion for active crowning (Eqn 4, CAC; Cruz *et al.* 2005; Alexander and Cruz 2006), a metric that evaluates whether predicted cROS (Eqn 4; cROS) exceeds a minimum cROS threshold based on crown bulk density (CBD) (Van Wagner 1977; Alexander and Cruz 2006).

$$I'_{initiation} = \left(\frac{CBH(460 + 25.9FMC)}{100}\right)^{3/2} \quad (2)$$

$$cROS_A = 11.02(U_{10})^{0.9} \times CBD^{0.19} \times e^{(0.17 \times FMC_{1hr})}, \quad CAC \geq 1.0 \quad (3)$$

$$CAC = \frac{cROS_A}{3/CBD} \quad (4)$$

Potential fire type was evaluated by combining I' and CAC using set theory in accordance with established fire type logic (Van Wagner 1977; Scott and Reinhardt 2001). Surface fire was assigned in cases where I_b was not capable of surface-to-crown initiation and cROS was not capable of crown-to-crown spread [$I_b < I'$, cROS < CAC]. Passive crown fire was assigned in cases where I_b was sufficient for surface-to-crown initiation, but cROS was not capable of crown-to-crown spread [$I_b \geq I'$, cROS < CAC]. Conditional crown fire was assigned in cases where I_b was not capable of surface-to-crown initiation, but

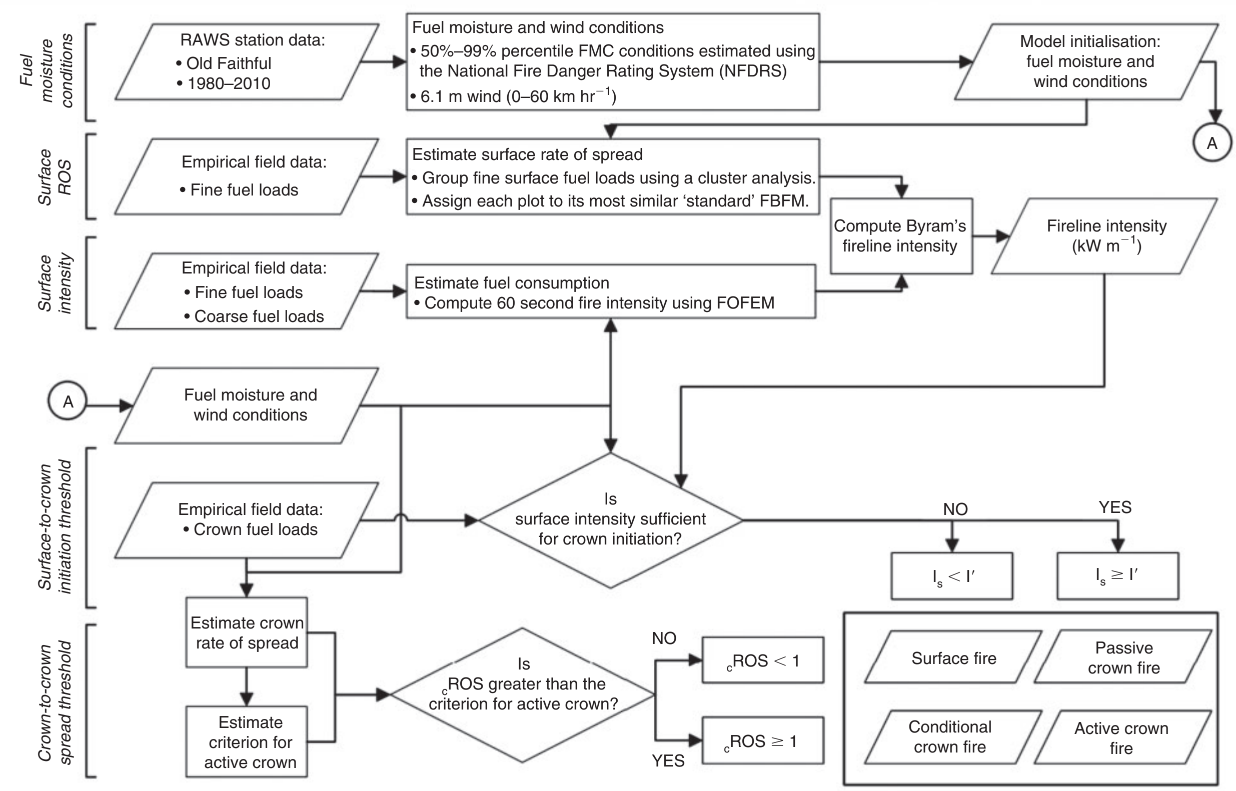

Fig. 1. Data and modelling work-flow used to predict surface and crown fire in 24-year-old lodgepole pine forests.

canopy fuel characteristics were sufficient for crown-to-crown spread [$I_b < I'$, cROS ≥ CAC]. Active crown fire was assigned in cases where I_b was sufficient for surface-to-crown initiation and cROS was sufficient for crown-to-crown spread [$I_b \geq I'$, cROS ≥ CAC].

Model parameterisation

Fuels

Empirical surface and canopy fuel characteristics from 82 stands of 24-year-old lodgepole pine (see Nelson *et al.* 2016) were used to parametrise our simulation model (Table 1). Thousand-hour fuel loads were resummarised and grouped into two decay classes, sound and rotten, and four log diameter classes corresponding to those required in the FOFEM – Burnup model (Albini and Reinhardt 1995, 1997): 7.5–15 cm, 16–22 cm, 23–50 cm, and >50 cm diameter classes. Canopy bulk density was computed using the mass over volume approach used by Van Wagner (1977) and recommended by Cruz and Alexander (2010). Fuels data can be found at http://dx.doi.org/10.5061/dryad.3b15s (accessed 6 May 2016).

Fuel moisture content (FMC)

Simulations were parameterised using FMC estimates spanning 50–99th percentile conditions (Fig. 1). Daily meteorological and fire occurrence data were downloaded via Kansas City Fire Access Software (KCFAST 2016) from the Old Faithful weather station (#480107) in YNP for all fire seasons (June–October) from 1981 through 2010. Percentile FMC conditions were generated for 1-h, 10-h, 100-h, 1000-h, herbaceous and shrub fuel classes using National Fire Danger Rating System protocols in the Fire Family Plus software system (Bradshaw and McCormick 2000). Live lodgepole pine FMC was estimated using a probability distribution of empirical FMC values from the Flagg Ranch station (1996–2012) in the National Fuel Moisture Database (NFMD 2016).

FMC declined in all fuel classes as the percentile (i.e. severity) of fuel moisture conditions increased in our simulation model framework (Fig. 2). Over the 50–99th percentile range in FMC conditions, herbaceous FMC declined from 79% to 3%, woody shrub FMC from 122% to 70%, 1-h FMC from 7% to 2%, 10-h FMC from 9% to 2%, 100-h FMC from 13% to 6%, 1000-h FMC from 17% to 10% and live lodgepole pine FMC from 118% to 84%.

Wind

Open wind speeds (6.1-m) were bound on the upper end at 60 km hr^{-1} representing 99.9th percentile wind speed at the Old Faithful Remote Automated Weather Station (RAWS) on fire days in YNP. Open wind speeds were converted to mid-flame wind speeds using sheltered and unsheltered wind adjustment factor (WAF) models depending on each stands empirical crown fill proportion (Eqn 5; *f*) where CC is canopy cover fraction and CR is crown ratio fraction (Table 1; Andrews 2012). The unsheltered model was used when *f* was less than 5% and the

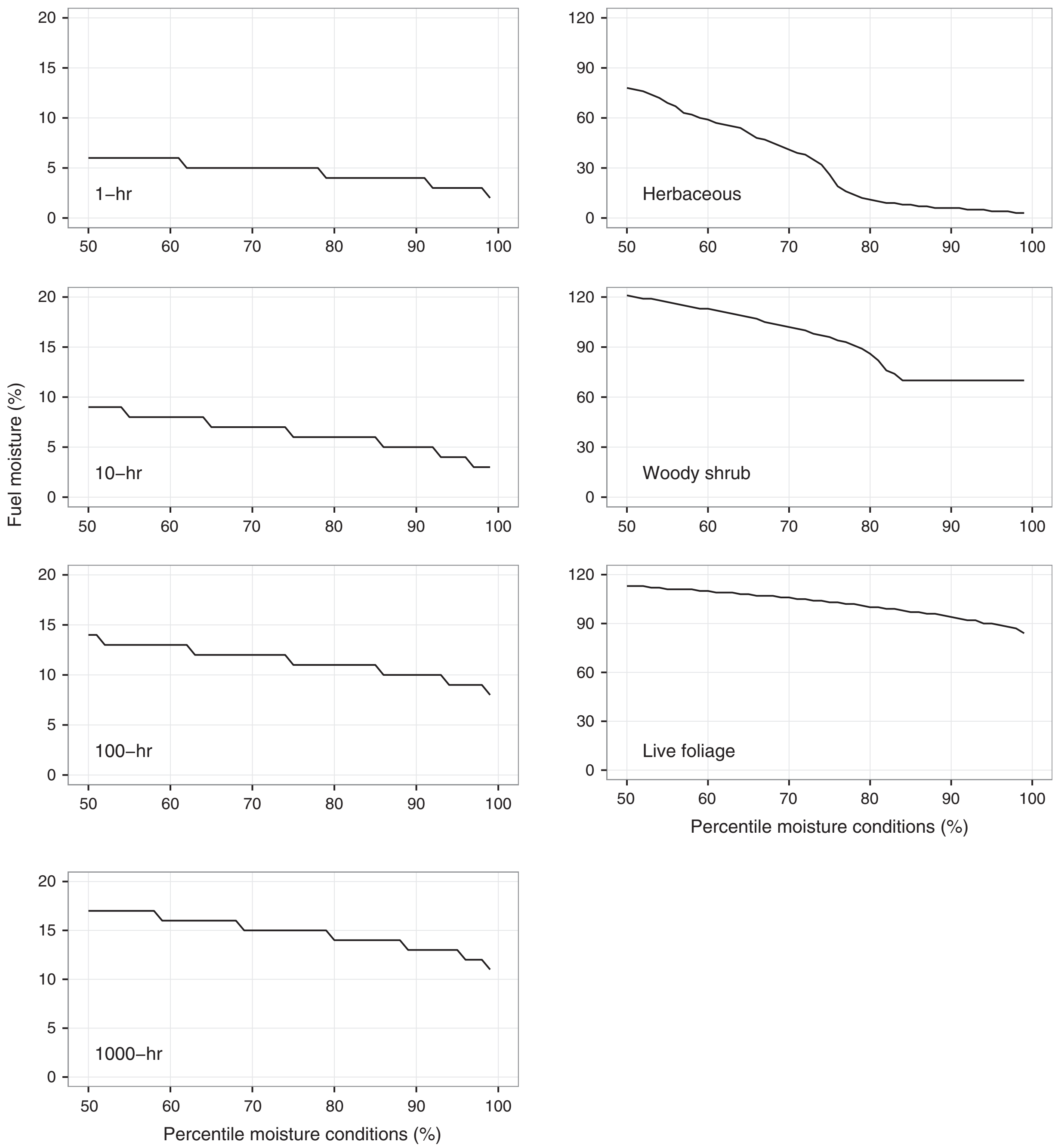

Fig. 2. Fuel moisture conditions over the fire season (i.e. June—October) in Yellowstone National Park (YNP). Fuel moisture content equals water mass divided by dry biomass and may exceed 100%. Surface fuel moistures were estimated using the National Fire Danger Rating System with data recorded at the Old Faithful RAWS station, YNP, Wyoming, USA for the period 1980–2010. All weather days were used to represent overall fire season conditions. Live lodgepole pine fuel moisture was estimated using data from the National Fuel Moisture Database recorded at the Flagg Ranch station for the period 1996–2012.

sheltered model was used when *f* was greater than 5%. Mid-flame wind was defined in the unsheltered case as the 'average wind speed from the top of the fuel bed to a height of twice the fuel bed depth' and in the sheltered case as 'constant with height under a uniform canopy layer' (Andrews 2012). Mid-flame wind speeds were used for input into the Rothermel surface fire spread model (Rothermel 1972, 1983). Wind dynamics in this study assume a uniform friction layer with adequate fetch (i.e. plots are independent of surrounding vegetation and their spatial context on the landscape).

$$f = CR \times (CC/3) \tag{5}$$

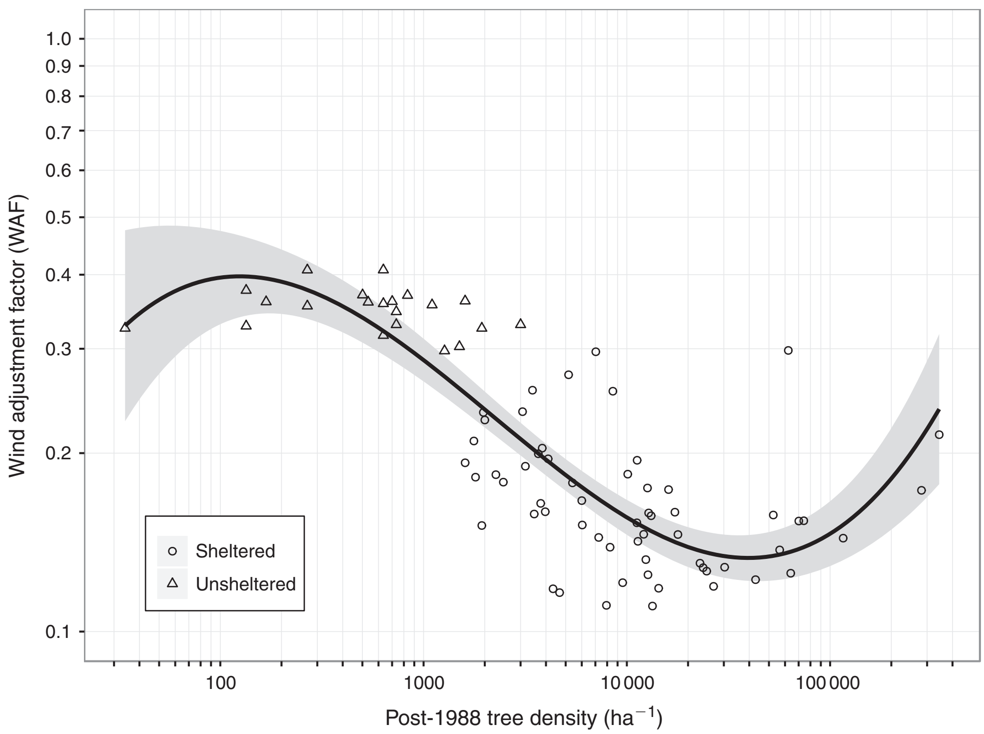

Fig. 3. Variation in modelled wind adjustment factor (WAF) with tree density.

Simulation experiment

Potential fire behaviour was simulated for each study site ($n = 82$) across a range of 50th–99th percentile fuel moisture conditions ($n = 50$ levels) and 1–60 km hr^{-1} open wind speeds ($n = 60$ wind speeds) resulting in 246 000 unique simulations. Potential fire behaviour output variables (Table 1) were simulated for each combination of fuel moisture, wind and site-specific fuel profile at the 1-ha scale.

Analysis

To quantify among-stand variation in potential fire behaviour in 24-year-old lodgepole pine stands, we computed the median and inner quartile range for HPA and I′, and generated boxplots (depicting median, interquartile range, and upper and lower observation at 1.5 times the inter-quartile range) for sROS and I_b at 50th and 99th percentile moisture conditions and 1, 25 and 50 km hr^{-1} open wind speeds. Binary canopy fire behaviour response variables were reported as percent of stands exhibiting surface-to-crown initiation or crown-to-crown fire spread at 50th and 99th percentile moisture conditions and 1, 25 and 50 km hr^{-1} open wind speeds. The distributions of fireline intensity and percent of stands exhibiting successful surface-to-crown initiation or crown-to-crown fire spread were plotted using a kernel density function.

Global sensitivity analysis was conducted to evaluate the sensitivity of model outputs to model inputs, and the contribution of model inputs and their interactions on model output variance. Partial rank correlation coefficients (PRCC) were used to evaluate input-output sensitivities because scatter plots indicated nonlinear, but monotonic relationships between input and output variables (Pianosi *et al.* 2016). PRCC indices with 95% confidence intervals and bias estimates were computed for WAF, HPA, I_b, I′, and cROS. The Extended Fourier Amplitude Sensitivity Test (eFAST) method was employed to assess first-order and total-order indices (Saltelli *et al.* 1999, 2008; Pianosi *et al.* 2016). First-order indices estimate the direct contribution of an input parameter on the output variance. Total-order indices estimate the overall contribution of an input parameter and its interactions with other parameters on output variance. Input and output variables are listed in Table 1. Because our complex model needed to vary iteratively, we emulated model behaviour by fitting a metamodel to our simulation dataset. Meta-model fit was evaluated by comparing predicted model output with observed model output using mean squared error (MSE) and RSME. Due to the high dimensionality of our simulation dataset, metamodel convergence and the estimation of sensitivity indices was computationally prohibitive using the full dataset. To overcome this, we used an optimised Latin hypercube sampling alogrithim (Saltelli *et al.* 2008) to produce a sparse set of wind and fuel moisture conditions where the mean distance between sample points was maximised taking into account the full range of sample points. All sensitivity tests were bootstrapped 999 times to estimate confidence intervals and error rates.

Analyses were completed using the R software program and the following r-packages: *base* (R Core Team 2016), *cluster* (Maechler *et al.* 2012), *DiceKriging* (Roustant *et al.* 2012), *DiceEval* (Dupuy *et al.* 2015), *dplyr* (Wickham and Francois 2015), *ggplot2* (Wickham 2009), *lhs* (Carnell 2016), *sensitivity* (Gilles *et al.* 2017), *spatialEco* (Evans 2016), and *Rothermel* (Vacchiano and Ascoli 2015).

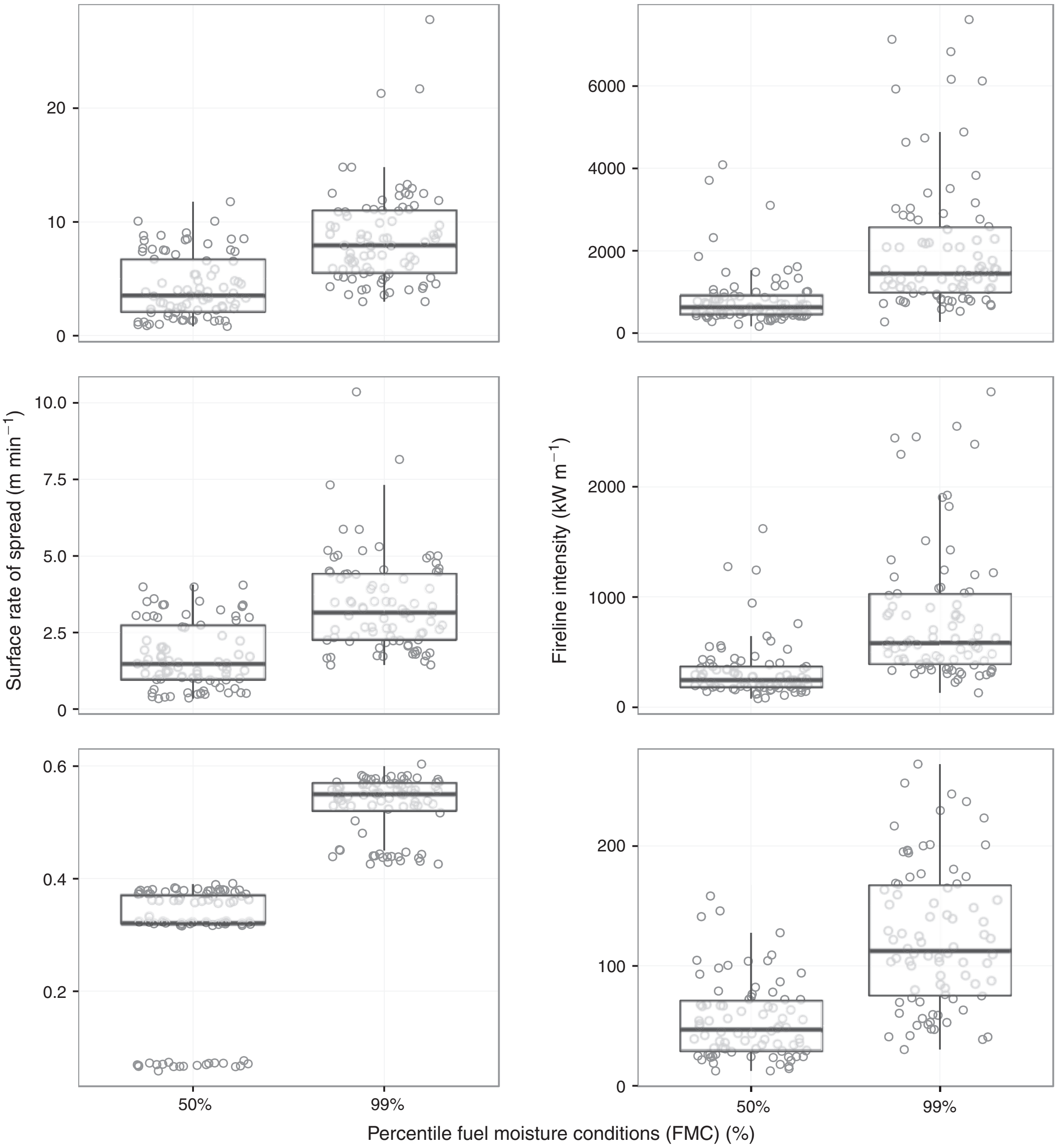

Fig. 4. Boxplots and site-level estimates for surface rate of spread and fireline intensity at 50th and 99th percentile fuel moisture and 1, 25, and 50 km hr^{-1} open wind speed (top, middle and bottom panels).

Results

Variation in potential fire behaviour

Potential fire behaviour varied among 24-year-old lodgepole pine stands depending upon surface and canopy fuel characteristics, fuel moisture conditions, and open wind speed. WAF ranged from 0.11 to 0.41 with 23 sites employing the unsheltered WAF model and 59 sites employing the sheltered WAF model (Fig. 3). At 50th and 99th percentile fuel moisture conditions, median and interquartile range for surface fire rate of spread (sROS) was 0.32 [0.32, 0.37] and 0.55 [0.52, 0.57] m min^{-1} at 1 km hr^{-1} and 3.52 [2.08, 6.69] and 7.91 [5.50, 11.01] m min^{-1} at 50 km hr^{-1} open wind speed (Fig. 4). Median HPA was 104.9 and 111.8 kJ m^{-2} under 50th and 99th percentile moisture (Table 2), and ranged from a minimum of 27.8 kJ m^{-2} to a maximum of 318.1 kJ m^{-2} depending on fuel load and composition. Critical surface-to-crown initiation intensity (I') varied from 0 kW m^{-1} in stands where canopy fuels contact surface fuels to 259 kW m^{-1} in stands with the greatest crown base heights (Table 2). At 50th and 99th percentile moisture conditions median and interquartile range for surface fireline intensity

Table 2. Median and interquartile range for heat per unit area (HPA) and critical surface-to-crown initiation intensity

HPA is the median intensity from the first 60 s of combustion in the First Order Fire Effects Model (FOFEM). Percentile moisture conditions represent probabilistic fuel moisture content (FMC) for fire seasons from 1981 to 2010 in Yellowstone National Park.

Percentile moisture conditions	Heat per unit area ($kJ\,m^2$)	Critical crown initiation intensity ($kW\,m^{-1}$)
50%	104.9 [65.9, 157.6]	49.9 [17.6, 91.6]
99%	111.8 [80.0, 164.7]	34.2 [12.1, 62.9]

(I_b) was 46.6 [28.9, 70.9] and 112.7 [75.3, 167.3] kW m^{-1} at 1 km hr^{-1} and 613.6 [440.1, 902.3] and 1449.3 [981.4, 2570.5] kW m^{-1} at 50 km hr^{-1} open wind speed (Fig. 4). The distribution of fireline intensity exhibited a strong positive skew that diminished slightly under 99th percentile moisture conditions (Fig. 5). Distributions of the percent of stands capable of surface-to-crown initiation and crown-to-crown spread were negatively skewed and increased under 99th percentile moisture conditions (Fig. 5). At 50th and 99th percentile moisture conditions, surface fire intensity was sufficient to overcome the surface-to-crown initiation threshold in 49% and 94% of stands at 1 km hr^{-1} and 99% of stands under all moisture conditions at 50 km hr^{-1} open wind speed (Fig. 6). The threshold for crown

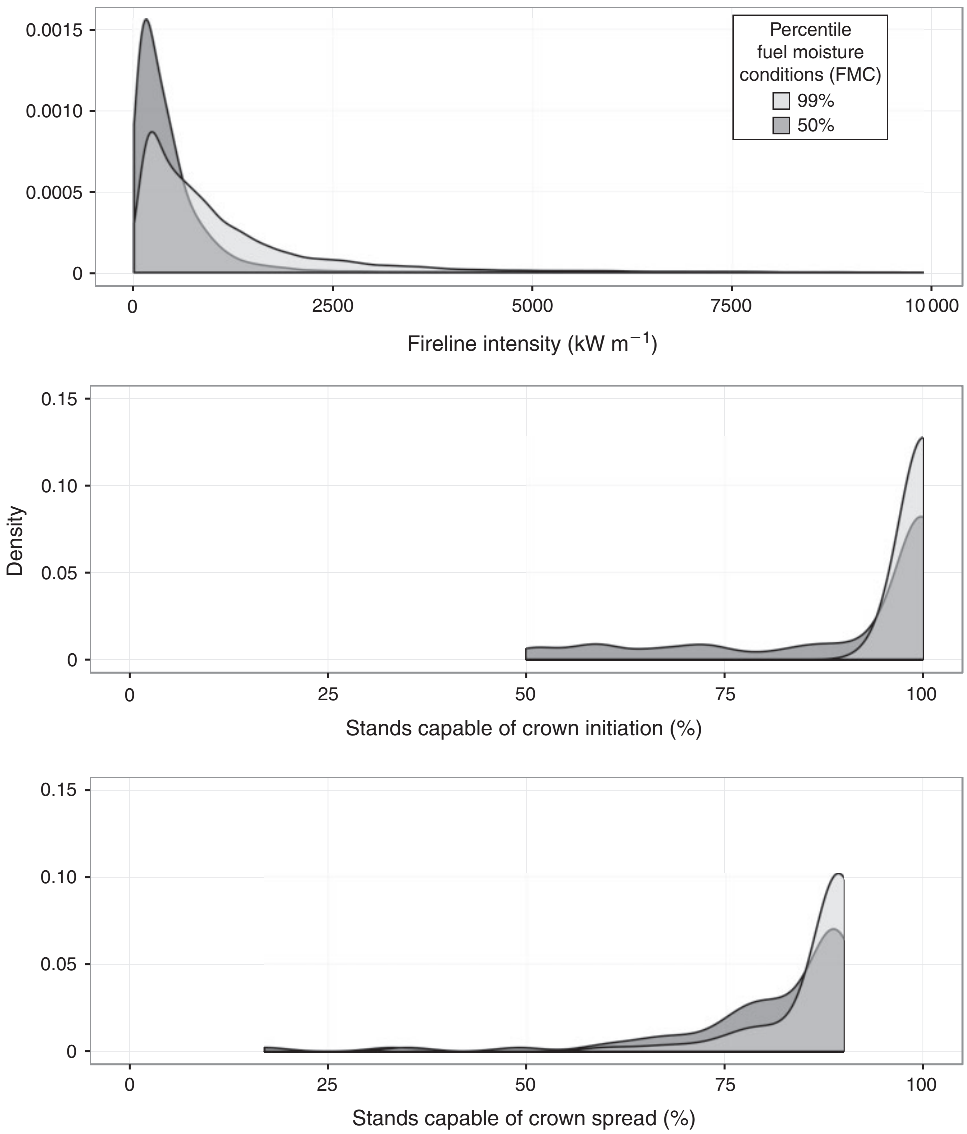

Fig. 5. Kernal density functions for simulated surface fire intensity, surface-to-crown fire initiation, and crown-to-crown fire spread at 50th and 99th percentile fuel moisture conditions.

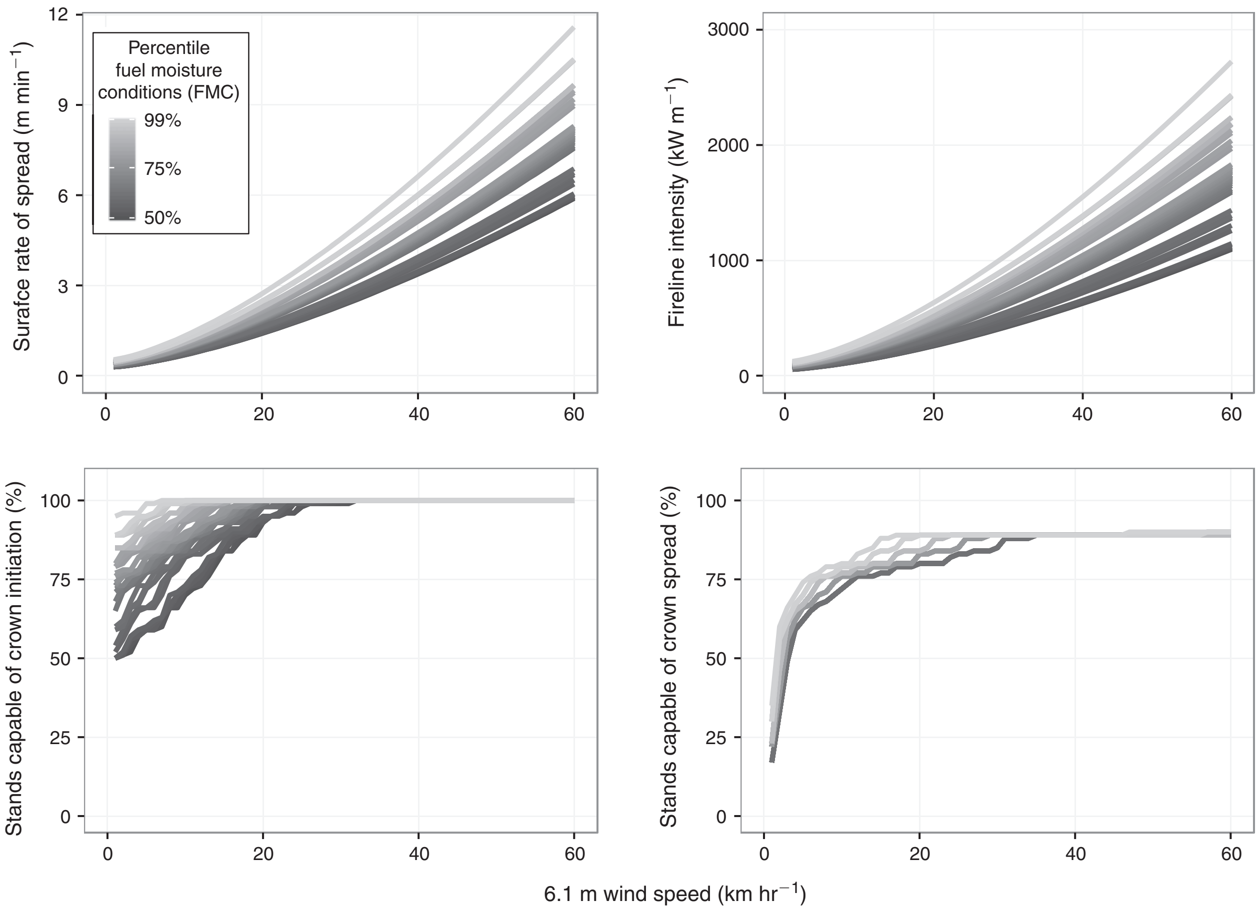

Fig. 6. Median surface rate of spread, fireline intensity, surface-to-crown fire initiation, and crown-to-crown fire spread across the full range of fuel moisture conditions and open wind speeds.

spread was met in a minimum of 17% of stands at 1 km hr^{-1} and a maximum of 89% of stands at 50 km hr^{-1} (Fig. 6). Even under extreme wind and fuel moisture conditions, 11% of stands were not capable of achieving spreading crown fire due to sparse tree cover and insufficient canopy bulk density.

Global sensitivity indices

Wind attenuation via WAF was primarily driven by two factors: crown area proportion and crown ratio (Table 3). Canopy cover was strongly and negatively correlated with WAF and contributed the most to output variance. Crown ratio did not globally correlate with WAF, but contributed a small amount to output variance. HPA model output from the FOFEM model was driven by two groups of factors: fine fuel groups and fuel moisture. Litter, 1-h, herbaceous and shrub fuel loads were all strongly and positively associated with HPA output with shrub fuel loads contributing the most and the other fuel types contributing much less to output variance. Fuel moisture in the 10-h and 1000-h fuel classes both contributed greatly to HPA output variance, but correlation coefficients were not significantly different from zero. I_b was driven via a positive correlation with WAF and shrub fuel load, a negative correlation with 1000-h fuel moisture, and weakly by 1-h fuel loads. WAF contributed the most to I_b output variance followed by shrub fuel loads, 1000-h fuel moisture, and 1-h fuel loads. I' was driven by a strong, positive correlation with crown base height that explained nearly all output variance. cROS was driven by a very strong, positive correlation with canopy bulk density, and a moderately strong, negative correlation with 1-h dead fuel moisture. Both input variables contributed a large share to output variance.

Model output

Simulation results predicted crown fire (e.g. passive, conditional or active types) in over 90% of stands at 50th percentile moisture conditions and wind speeds greater than 3 km hr^{-1} (Fig. 7). The prevalence of passive crown fire varied inversely with wind speed, declining from a maximum of 49% and 61% of stands at 1 km hr^{-1} wind speeds under 50th and 99th percentile moisture to a minimum of 11% of stands at 35 km hr^{-1} under 50th percentile moisture and 17 km hr^{-1} under 99th percentile moisture (Fig. 7). Conditional crown fire was possible in the greatest percent of stands (i.e. 40%) at 6 km hr^{-1} and 50th percentile moisture; however, this value declined sharply to a minimum of 1% of stands at 26 km hr^{-1} (Fig. 7). At wind speeds greater than 10 km hr^{-1} and fuel moistures greater

Table 3. Global sensitivity indices estimating the sensitivity of model outputs to model inputs (PRCC) and the contribution of inputs to model output variance (eFAST)

First-order indices estimate the direct contribution of an input parameter on the output variance and total-order indices estimate the overall contribution of an input parameter and its interactions on output variance. Statistical differences reflect 95% bootstrapped confidence intervals. Shown here are input parameters that contribute >1% to output variance. Sensitivity indices for all input parameters are shown in Supplementary Table 1.

		Partial Rank Correlation Coefficients (PRCC)		Extended Fourier Amplitude Sensitivity Test (eFAST)	
Output variable	Input parameter	Mean (95% CI)	Bias	First order	Total order
Wind adjustment factor (WAF) (fraction)	Canopy cover (fraction)	−0.858 (−0.930, −0.798)	−0.002	0.634	0.869
	Crown ratio (fraction)	0.058 (−0.171, 0.379)	−0.022	0.121	0.298
Heat per unit area ($kJ\,m^{-2}$)	Litter ($Mg\,ha^{-1}$)	0.989 (0.987, 0.991)	0.000	0.017	0.020
	1-hr ($Mg\,ha^{-1}$)	0.099 (0.036, 0.168)	0.000	0.040	0.051
	10-h fuel moisture (%)	−0.011 (−0.077, 0.062)	0.001	0.445	0.471
	1000-h fuel moisture (%)	−0.058 (−0.129, 0.012)	−0.001	0.120	0.130
	Herbaceous ($Mg\,ha^{-1}$)	0.735 (0.710, 0.762)	0.001	0.013	0.016
	Shrub ($Mg\,ha^{-1}$)	0.239 (0.176, 0.307)	−0.002	0.323	0.350
Fireline Intensity† ($kW\,m^{-1}$)	1-h ($Mg\,ha^{-1}$)	0.000 (−0.069, 0.068)	−0.001	0.014	0.025
	Shrub ($Mg\,ha^{-1}$)	0.139 (0.069, 0.215)	−0.002	0.170	0.263
	1000-h fuel moisture (%)	−0.244 (−0.309, −0.177)	−0.001	0.028	0.048
	WAF (fraction)	0.643 (0.601, 0.686)	0.001	0.641	0.760
Critical crown fire initiation intensity ($kW\,m^{-1}$)	Crown base height (m)	0.999 (0.999, 0.999)	0.000	0.997	0.999
Crown fire rate of spread (cROS) ($m\,min^{-1}$)	Crown bulk density ($kg\,m^{-3}$)	0.946 (0.936, 0.959)	0.000	0.556	0.564
	1-h fuel moisture (%)	−0.415 (−0.481, −0.347)	0.000	0.434	0.435

† The following large log classes were removed from the fireline intensity sensitivity analysis to reduce the dimensionality of the dataset and is justified by their lack of contribution to output variance in the heat per unit area sensitivity analysis: sound logs 16–22 cm diameter, sound logs 23–50 cm diameter, rotten logs 23–50 cm diameter, and rotten logs >50 cm diameter.

than 90%, conditional crown fire was superceded by active crown fire in 90% to 98% of stands. Active crown fire was predicted in 50% of stands at 13 and 2 $km\,hr^{-1}$ under 50th and 99th percentile moisture conditions, and was present in the maximum percent of stands (i.e. 88%) at 35 and 17 $km\,hr^{-1}$ wind speeds (Fig. 7).

Discussion

Simulation results from this study suggest a high potential for crown fire behaviour across the diversity of fuel conditions found in 24-year-old lodgepole pine stands originating after the 1988 Yellowstone Fires. Recent fires in YNP provide clear evidence that extensive burning is possible in young lodgepole pine forests. High propensity for crown fire activity is no surprise under extreme fuel moisture and wind conditions; however, we found that most stands sampled in this study met model criteria for passive, conditional, and active crown fire under far lesser conditions. If young forests expand as expected over the next century due to increased fire activity, an expansion of heightened crown fire potential associated with young forests will pose an increased risk to firefighting personnel, human infrastructure and ecosystem services.

It is well established that coniferous forests can burn as active crown fires under extreme weather conditions; what is new, and somewhat surprising, about the results of our study is that crown fire behaviour is possible, even likely, in 24-year-old lodgepole pine forests under moderate as well as extreme fuel moisture and wind conditions. A major driving factor of modelled crown fire in these systems is the dominance of dense canopy conditions in close proximity to surface fuelbeds. Modification of canopy fuel loads and structure have been found to be effective in mitigating crown fire risk, especially under the less than extreme weather conditions in which most wildfires occur (Agee and Skinner 2005). Given the strong, positive effect and large contribution to output variance that canopy bulk density has on crown fire rate of spread estimates, we anticipate that management interventions in young lodgepole pine forests focussed on decreasing or breaking up dense canopy conditions can help to mitigate crown fire risk in these stands.

Sensitivity analysis indicates that wind attenuation was most important in predicting surface fireline intensity, canopy fuel conditions were most important in driving wind attenuation (i.e. WAF) and surface-to-crown initiation, and canopy fuel conditions paired with 1-h surface fuel moisture were most important in driving crown-to-crown rate of spread. Past studies investigating large fires in boreal and subalpine forests found the primary driving factors to be associated with severe weather conditions including high winds and low fuel moisture conditions (Lotan *et al.* 1985; Turner *et al.* 1994; Bessie and Johnson 1995; Schoennagel *et al.* 2004). Our fire behaviour model results

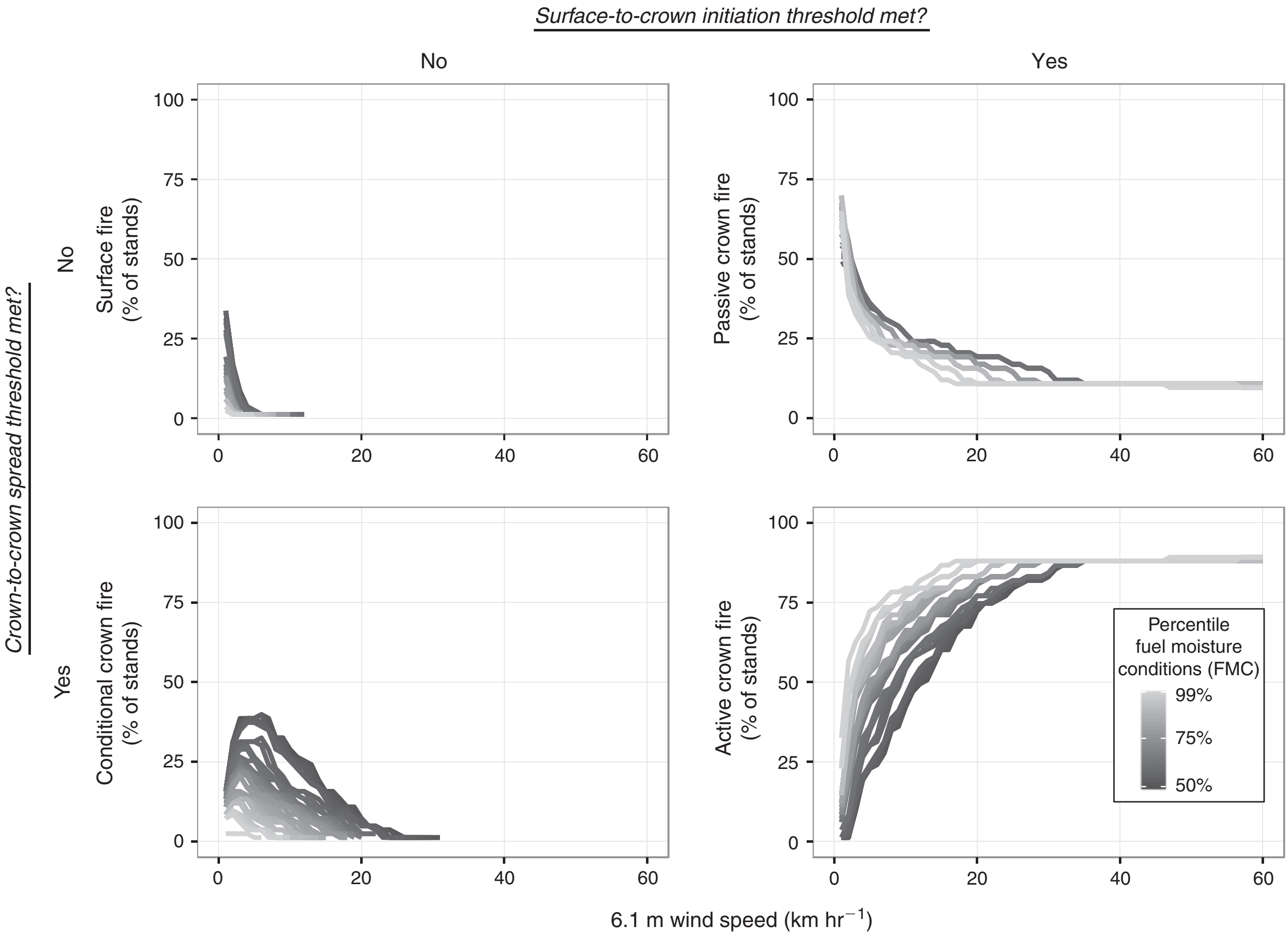

Fig. 7. Percent of stands predicted to achieve each fire type by percentile moisture conditions and 6.1-m open wind speed. Fire types were determined by contrasting the surface-to-crown and crown-to-crown fire thresholds for each stand using Boolean logic and include: surface fire, passive crown fire, conditional crown fire and active crown fire (Van Wagner 1977; Scott and Reinhardt 2001).

from young post-fire lodgepole pine forests indicate that dense, low stature canopy conditions may substantially lower wind speeds required for crown fire initiation and spread. Decreasing fuel moisture systematically shifted fire model estimates towards more severe burning conditions and increased the rate of stands estimated to achieve crown fire. Our findings emphasise the relative contribution of canopy fuel characteristics over wind and moisture conditions in young, closed canopy lodgepole pine forests.

Fireline intensity and sROS estimates were similar or lower than other studies conducted in young coniferous forest types. sROS values from this study were ~10% of values observed in experimental fires in 27- to 33-year-old Jack pine (*Pinus banksiana*) stands with higher fuel loads in Ontario, Canada (Stocks 1987), ~30% of those modelled in 1-, 3- and 19-year-old western hemlock/Douglas-fir (*Tsuga heterophylla*/*Pseudotsuga menziesii*) stands with greater fuel loads in Washington, US (Agee and Huff 1987), but similar to observed sROS in Swedish Scots pine/Norway spruce/birch (*Pinus sylvestris*/*Picea abies*/ *Betula* spp.-) boreal forests <25 years old with similar fuel loads (Schimmel and Granström 1997) and modelled sROS in one year postfire mixed-conifer forest with heavy uncombusted ground fuel loads in the Cascade Range, US (Hudec and Peterson 2012). Observations of crown fire spread in young forests were not available for comparison; however, open wind speeds associated with crown fire activity in this study (Fig. 7) fell within the range of wind speeds observed during crown fires across western North American conifer forests (Cruz and Alexander 2010).

Our analysis provides improved understanding of potential fire behaviour in young forests under less extreme conditions, but is constrained by the assumptions and formulation of existing operational fire models. Model formulation presented here adheres to the long-standing tradition of linking surface fire intensity to the ignition and spread of crown fire (Van Wagner 1977; Cruz *et al.* 2004). Fireline intensity (I_b), as modelled in this study, reflects the product of HPA and sROS. A recent review found that underestimates of fireline intensity are pervasive in operational fire modelling software and may exaggerate wind speeds required for crown fire initiation due to systematically low approximations of HPA (Cruz and Alexander 2010). To overcome this issue, we estimated HPA using 60-s median fire intensity calculated in FOFEM. This doubled I_b estimates when compared with the commonly used residence time method, and successfully resulted in shifting estimates of crown fire initiation to lower wind speeds where crown fires in coniferous fuel types have been observed (Cruz and Alexander 2010). sROS was estimated from standard FBFMs selected using a cluster analysis. Head fire observation data is required for empirical bias estimates but was not available in our specialised fuel type (but see Miller *et al.* 2009). Further research is required to compare HPA estimates using 60-s median fire intensity from FOFEM against other methods (e.g. Nelson 2003), and improve the integration of these fire modelling systems for use in novel fuel beds.

The method we used for estimating FMC inputs may nominally depress estimates of surface fireline intensity and surface-to-crown fire initiation. Reference live and dead FMC were estimated using empirically-based methods for mature forest stands with the assumption that the ranges and probability distributions of FMC are analogous in young and mature stands. Recent research in YNP showed that dead FMC did not differ between young and mature stands during the 2014 fire season, except in response to heavy precipitation (Nelson 2017). Live foliar fuel moisture varied over the same range in young and mature forests; however, the timing of low and high fuel moisture was offset due to accelerated snowmelt and earlier soil water use in young stands. We do not anticipate major deviations in reference fuel moisture conditions computed using the probability distribution approach; however, earlier drying in young, post-fire stands may lead to a minor shift in the distribution towards drier conditions.

Heterogeneity in stand structure and fuel characteristics at within and among plot spatial scales may lead to deviations in predictions made using operational modelling frameworks (e.g. Parsons *et al.* 2017). Operational fire models deterministically predict central tendency fire behaviour at the expense of assuming homogeneous fuel characteristics and moisture conditions at the plot scale. Within plot fuel clumping can affect localised fuel loads and fuel moisture, and may lead to anomalous fine-scale fire behaviour that is lower or higher than predicted in our model. While not directly linked to model formulation, among plot heterogeneity in the way of landscape complexity may lead to deviations away from model predictions by changing boundary layer conditions and plot-level wind dynamics (Beer 1991). This issue is of particular concern near young–mature forest edges and vegetation type boundaries, and is most likely to occur when wind and weather conditions are not extreme. Incorporating spatial heterogeneity in fire prediction is the subject of current research using computational fluid dynamics models (e.g. the Wildland-Urban Interface Fire Dynamics Simulator (WFDS) and HIGRAD/FIRETEC models); however, recent advances in ensemble modelling using operational fire models may also be useful in investigating assumptions related to spatial heterogeneity in fire model prediction (Cruz and Alexander 2017).

In summary, simulation results suggest that young forests with prolific post-fire tree regeneration exhibit substantial crown fire potential even under low to moderate wind and fuel moisture conditions. Sensitivity analysis indicates crown bulk density as the primary factor driving heightened crown fire potential. Therefore, management interventions aiming to reduce or redistribute canopy fuels may be effective in reducing crown fire hazard, especially under moderate burning conditions. The hazard reduction may only be temporary, of course, for remaining trees will continue to grow, and new trees may become established.

Conflicts of interest

The authors declare they have no conflicts of interest.

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