Fire regimes for risk management of koalas on the NSW Southern Tablelands

Report to the NSW Office of Environment and Heritage

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Executive summary

This report is an analysis of the most effective fire regimes for protection of koala (*Phascolarctos cinereus*) populations in the Southern Tablelands study area. These were determined through analysis of the vegetation dynamics using the Fire Research and Modelling Environment (FRaME) – a tool being developed for the NSW Office of Environment and Heritage to quantify flammability dynamics and the risks that fire poses to wildlife.

In an intensive field survey of southern tablelands dry sclerophyll forest at different stages of regrowth from low-severity fire, the main dynamic detected was in the shrub layer. Plants increased in size for about two decades, but continued to thin indefinitely in a linear trend. FRaME analysis of this predicted a pronounced positive feedback, where flames were largest at 10-years post-fire and then decreased in size as the forest matured. Relative to older forests, fires were modelled to be over twice as difficult to contain for about three decades after a prescribed burn. These findings are consistent with empirical studies, which give a 10-year peak in flame size across many dry sclerophyll forests, and predict a 2-3-fold increase in flammability for regrowing forests. The measured feedback is slightly stronger than the modelled one, however, this was expected as it included the effects of high severity events.

To investigate the mechanisms by which high severity fire affected these dynamics, I performed a FRaME analysis of the depth and intensity of soil heating and seedbank disturbance in high vs. low-severity events. The negligible differences in heating suggest that this is not a causal factor, implying that canopy loss itself is the critical issue.

As well as being more difficult to contain, the larger and slightly slower-spreading flames of young forests were expected to cause greater heat penetration to the upper parts of trees where koalas roost, making them more likely to be burned or killed, and increasing the risk of canopy foliage loss to scorch.

For these reasons, prescribed burning is not recommended in these forests. Relative to equivalent natural-fire-only scenarios and depending on the frequency of introduction, the combination of natural fire supplemented by prescribed burning produces a 4 to 8-fold increase in the risk of 2nd degree burns to koalas, a 5 to 12-fold increase in the risk of 3rd degree burns, and creates the likelihood of direct mortality where it would not exist if the forest was left in its long-unburnt state. The likelihood of scorching more than 50% of the canopy was also increased 11 to 16-fold

Two recommendations are therefore made:

1. Unless values other than hazard reduction and risk reduction to koalas necessitate it, fire should not be intentionally introduced to the study area.

2. Rapid fire suppression should be prioritised for the study area. To assist with this, fire authorities should consider designating Strategic Fire Advantage Zones for more aggressive fire exclusion. Work is underway concurrent to this study (Parkins *et al*[1]) to inform the design and location of these.

Introduction

The goal of this analysis is to identify the fire regimes that pose the lowest threat to koala populations in the Southern Tablelands study area (Fig. 1). This was conducted as part of the Environmental Trust project 2017-RD-0139 “Modelling fire risk to fauna”.

The analyses in the study complement those in the study ‘Fire risk management of populations of the koala *Phascolarctos cinereus* in the NSW southern tablelands: A simulation study’[1]. While that study examines the likelihood of fire impacting on koala habitat given the placement of hazard reduction treatments, the current report aims to identify which treatments will be the most effective in reducing that hazard. Here, I quantify the risk to koalas and the capacity for fire control that results from different prescribed burning frequencies ranging from a five-year burning rotation through to fire exclusion.

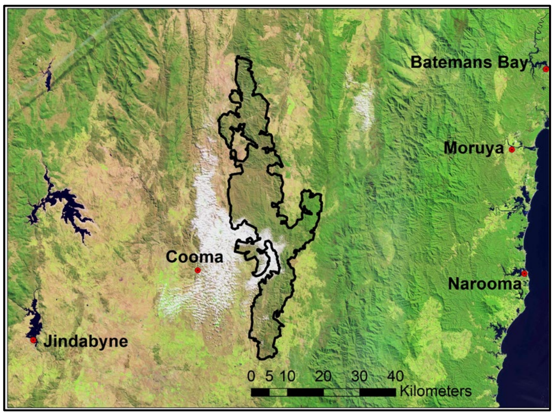


Figure 1 | Southern tablelands study area.
Background image Landsat 8, April 19th 2019.
Source: https://earthexplorer.usgs.gov/

Methods

This is a modelling study that utilises FRaME (Fire Research and Modelling Environment) software being developed for the NSW Office of Environment and Heritage. FRaME is an implementation of the Forest Flammability Model[2] within the R Statistical Environment[3], intended to provide calculations of higher resolution and accuracy for fire behaviour and consequent threat to fauna. FRaME differs from models in current operational usage for eastern Australia in that the core model has been peer-reviewed, is able to provide ecosystem-specific results, and directly calculates specific threats to the fauna being examined. Models based on fuel load are constrained to predict a negative feedback where flammability increases over time in correlation with the increase in fuel load, despite the fact that feedbacks are known to be positive (mature forests are less flammable) in many ecosystems. Management that incorrectly assumes negative feedbacks will produce perverse outcomes where fire risk is increased rather than decreased, potentially leading to species loss or ecosystem collapse[4,5]. The correct identification of feedback direction and strength is therefore central to effective fire management, and the Forest Flammability Model provides a means to do so[6] that cannot be achieved using traditional operational models.

Vegetation

The vegetation for the study site is dominated by Southern Tablelands Dry Sclerophyll Forest[7], a predominantly open forest of *Eucalyptus rossii* and *E. macrorhyncha* over a grassy *Joycea pallida* layer with scattered shrubs such as *Cassinia longifolia* and *Daviesia mimosoides* (Fig. 2).

Figure 2 | Southern tablelands dry sclerophyll forest

Analyses

Two analyses were performed:

1. Flammability dynamics
2. Risk assessment

Flammability dynamics

Flammability dynamics refers to the changes in contextual flammability with time since fire. This is the flammability of the vegetation within its local context, and within the context of the values being considered. This contrasts with approaches that measure flammability against standardised weather conditions for example, providing more meaningful measurements for decision making for a specific site[8].

To define the climatic context, I modelled fire behaviour for the 2pm weather conditions recorded at the closest weather station (Cooma airport), for the summer 2018-19 months. I modelled dead fuel moisture content (DFMC) mechanistically[9] to account for rainfall effects, and assumed an extinction moisture content of 20%.

To characterise the forest, I used data from a survey of STDSF that I had conducted with a team from CERMB and ANU in 2014 and 2015. Measurements of stands aged from 0 to 34 years after what had been mostly prescribed burns provided sufficient data to model changes in vegetation with time. Where possible, equations were fit to the average values for each age class, and these were then entered into FRaME to run a flammability dynamics analysis. Where no trend could be identified, the long-term mean value for the trait was used.

The analysis modelled 10 randomised replicates of fire behaviour for every day of weather, growing the forest in annual increments from 1 to 70 years post-fire. I summarised the modelled fire behaviour into flame height and rate of spread (ROS), then summarised these into the average likelihood that direct attack methods of fire-fighting will be unsuccessful due to flame height or rates of spread. Australian fire fighters utilise a series of cut-off points for fire-fighting attack methods based on flame height, so that direct attack is only recommended for flames up to 1.5m in height[10]. Research elsewhere has shown that rates of spread also limit the success of initial attack operations, so that fires spreading at 2m/min (0.12km/h) are contained approximately half as often as the maximum level of containment success[11]. These values were therefore combined so that direct attack was counted as successful if flame heights were not more than 1.5m, while spreading at not more than 0.12km/h.

Fire severity effects

Previous empirical analysis for the Australian Alps bioregion[8] has identified that dry sclerophyll forests are markedly more flammable during their regrowth period than when mature, however the causal mechanisms for this have not been thoroughly investigated yet. These values also represented the average response to all fires, whereas fire management studies are frequently more interested in the response to low-severity planned fires. It is likely that high severity fires will have a more pronounced effect on the feedback, as they cause a greater scale of change[8] through the removal of canopy foliage. In some environments, high severity fires also promote greater density of shrub germination[12]. In the context of STDSF, germination is known to be stimulated for many species through soil heating and the removal of surface litter[13], however, the degree of soil heating is not necessarily related to fire severity[14].

Given that the data on post-fire regeneration in this study was almost entirely limited to sites disturbed by prescribed fire (assumed to be low intensity), it is not possible to quantify how higher-severity fire might affect recovery. In lieu of this, FRaME was used to model the degree of soil heating and its expected effects on seed germination for dominant shrub species. This was used to compare the quantity of topsoil likely to have been heated to a point where germination was stimulated or the seed-bank destroyed, comparing fires burning under mild conditions across the slope (simulating a low-severity prescribed burn), with fires burning up a 20^{o} slope under the more severe conditions expected for wildfire scenarios.

Previous work has indicated that heat conduction into soils is related to the weight of dead organic material burning on the soil surface[15]. The physics of heat transfer however allow for other drivers that may become important under conditions of stronger wind or steep terrain. FRaME accounts for these, modelling the direct conduction of heat from burning surface materials, but adding to this heat transferred through radiation from the flame, and convective transfer occurring when wind-driven flames lie flat against steep slopes (flame attachment).

Other site variables also affect soil heating. Soil texture and organic content affect heat conduction[16,17], and soil water content imposes a barrier to heat penetration due to the latent heat of vaporisation. This is a complex process, however, as soil moisture also affects the likelihood of seed survival and data does not necessarily exist for the relevant species[18]. Moisture was therefore kept constant (5%), organic material assumed to be 10% due to lack of published data, and heat effects on germination were analysed accounting only for differences in soil texture.

Two thirds of the study area is covered by three soil landscapes, all dominated by some form of loam[19,20] (Table 1).

Table 1 | Soil landscapes. Dominant soil landscapes in the study area.

Landscape	Area	Landform	Texture
Foxlow	29%	Steep terrain	Sandy loam, sandy clay loam
Macanally Mtn	27%	Gentler terrain	Loam, Light sandy clay loam
Schofield's Ck	13%	Low hills	Loam, Sandy loam, Clay loam

I analysed three contrasting textures of loam – sandy loam, loam, and clay loam. Two questions were examined in this context:

1. Are shrub species encouraged by soil heating?
2. What is the depth of soil heating vs. seed-bank destruction in mild fire conditions compared to very high fire conditions?

Risk assessment

The risk to koala populations derives from both the likelihood of fire occurrence, and the consequence when it occurs.

Likelihood

Fire likelihood was estimated from the expected fire frequency, so that likelihood is equal to 1/frequency. Mapped fires for the area have been collected from departmental records and through public meetings conducted as part of the NPWS fire management strategy process, yet these records note only a few events and indicate that the majority of the area has remained unburnt for at least living memory. In the absence of better data then, an average value of 50 years was adopted to represent the background fire frequency.

Background frequency was modified for each scenario according to changes resulting from fire management, so that treatments which reduced the flammability reduced the expected frequency, and increases in flammability increased the frequency. While such changes are affected by the broader landscape, previous empirical work has identified that meaningful generalisations can be made at the point scale using the flammability ratio FR[8], which is the likelihood of fire at a point relative to the overall mean. An FR of 2 for example means that a site is twice as likely to burn compared to the average likelihood from 1-50 years.

FR has been calculated empirically for dry open forests including STDSF, where time since fire accounts for more than one third of the likelihood that a point will burn[8]. Rather than depend on this broader generalisation however, this study utilised the outcomes of the fire dynamics modelling to approximate the FR specific to STDSF, resulting only from vegetation changes caused through prescribed burning. Rates of direct attack failure were converted to an approximation of the flammability ratio (pseudo FR FR_{ps}), by dividing the individual direct attack failure rates by their 50-year mean, then this data was approximated by a function to generalise the trend. Finally, average FR_{ps} values were taken from the function for 5, 10 and 20 year periods measured from directly post-fire to find the mean flammability for three different prescribed fire frequencies, and from 50 years post-fire to find the mean flammability for the three alternative treatments of fire exclusion.

Consequence

Fire threatens faunal populations through both immediate mortality and injury leading to mortality, and through modifications to habitat that cause consequences such as the loss of food sources or expose the animals to predators[21]. Longitudinal studies indicate that predation by dingoes or dingo hybrids accounts for 52% of koala deaths on average[22], however, links to vegetation structure and predation are currently weak[23]. This may be due in part to complex interspecific association. Studies in the US for example have identified that due to the "leapfrog effect" where predator numbers increase in environments providing improved prey habitat, shrub density is positively related to coyote (*Canis latrans*) dominance despite the cover it affords to prey species.

FRaME models the immediate consequence of fire to koalas by finding the amount of heat transferred to the animals as flames pass beneath the tree in which they are sheltering (Fig. 3). Heat transfer from both radiation and convection along with conduction through the fur is calculated using standard heat transfer physics. This is then used to calculate the *thermal dose*[24,25], which determines the degree of damage to the animal, ranging from pain through to third-degree burn or death.

The level of impact from the fire depends largely on the behaviour of the animal. When threatened by fire, koalas in this study are assumed to climb to the highest parts of trees where branches are still large enough to support their weight; this is set at eight metres. More broadly, koalas are physiologically stressed by hot, dry conditions[26–28] and respond by seeking shelter in the cooler microclimates provided by gullies[29]. This is likely to mean that koalas are not present on ridges during the hottest summer weather when wildfires are most likely due to widespread dry fuels, and this may provide some degree of protection. Without quantification of this behaviour however, it cannot be incorporated into this study and the risk proposed by summer wildfires may be overestimated.

Without firm data, it is difficult to predict the survival rates of koalas given different burn injuries, so three different thresholds were calculated in this study. In addition to direct burn injuries, koalas are also injured or killed

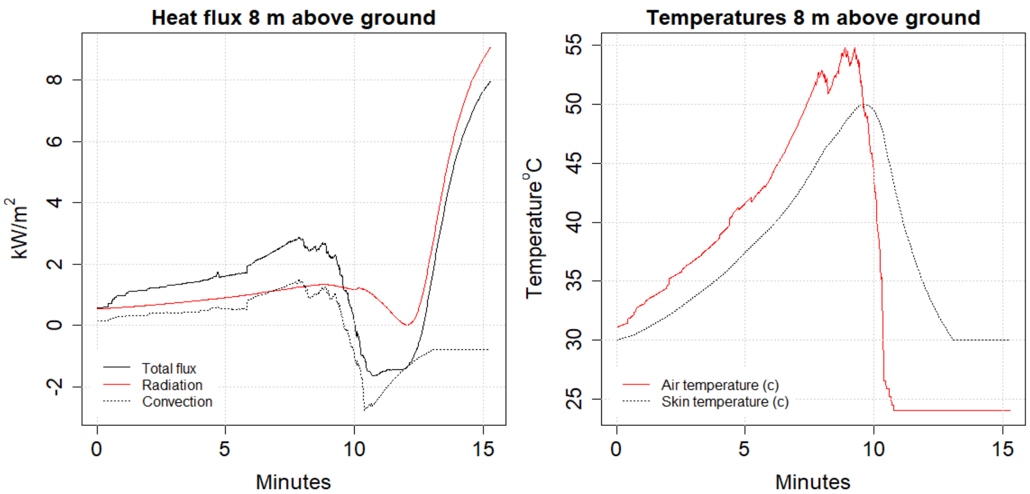


Figure 3 | Dynamic heating output from FRaME. Example taken from the 80th percentile of wildfire behaviour in 10-year-old forest, showing heat fluxes modelled from radiation and convection in the left-hand panel, and the comparison between air and skin temperature on the right. The sharp rise in radiative heat flux after about 12 minutes represents heating *after* the fire front has passed, resulting from the fact that a forward-leaning flame exposes a greater radiating face from this angle. This scenario produced 2nd and 3rd degree burns, but no direct mortality.

through smoke inhalation and burns to hands and feet from hot tree trunks[30]. As important as these factors are, they cannot yet be modelled by FRaME due to insufficient knowledge of the risk factors, so all consequence calculations should be regarded as conservative.

The consequences of fire on koalas and their habitat were modelled for forests burnt by low intensity fire 5, 10, 20 and 50 years previous, under both mild and very high fire danger conditions. Weather conditions were taken from the closest weather station of similar altitude at Cooma airport, dead fuel moisture content was modelled mechanistically as for flammability dynamics, and 20 replicates were calculated for each time step.

The 'mild' scenario was selected to represent ideal prescribed burning conditions. Weather records from autumn 2018 (BOM online http://reg.bom.gov.au/climate/dwo/IDCJDW2171.latest.shtml) were accessed to find a day in which DFMC was below the extinction threshold of 20% oven dry weight, wind speeds were below or close to 10km/h, and at least two days followed with low wind speeds or significant rain. To capture the diversity of conditions, hourly weather inputs were first interpolated by fitting a spline to the available 9am and 3pm values. To simulate a low-severity ignition pattern where ignitions are in lines running down-slope to produce cross-slope spread, the slope for this scenario was set to 0 (cross-slope).

The high fire danger scenario was chosen by selecting the windiest summer 2018-19 day from those days in which DFMC was low enough to allow fire spread. To represent wildfire conditions, these simulations were run up a 20^{o} slope.

For each scenario, I found the percentiles for which 2nd degree burns ,3rd degree burns or death were more than 50% likely. This provided three levels of risk assessment, describing the percentage of a burn footprint for which partial thickness burns, full thickness burns or immediate death were the most likely outcome.

The long-term threat to koala populations is a complex ecological question requiring detailed population viability analysis in the context of nutritional requirements, predator populations and other drivers. While such modelling is beyond the scope of a fire behaviour analysis, FRaME provides detailed metrics of fire impact from which this can be calculated. These are summarised here into the likelihood of scorch or consumption of each plant stratum.

Loss of tree crowns through scorch or consumption results in the loss of feed for up to three months after fire[31], so this metric was summarised by the likelihood of ≥50% crown scorch.

Risk calculation

The quantified risk of each scenario was found by combining likelihood and consequence for wildfire (L_w, C_w) and adding these to likelihood and consequence for prescribed fire (L_p, C_p):

$$L_w C_w + L_p C_p \qquad \text{Eq. 1}$$

Two treatment options were calculated for each scenario: fire introduction and fire exclusion. Annual risk was therefore calculated for six treatments in three scenarios.

Results

Flammability dynamics

Forest dynamics

No significant changes in cover or height were detectable for the *Eucalyptus rossii* - *E. macrorhyncha* trees or saplings, however, *Joycea pallida* grasses recovered to pre-fire heights within a few years of fire (Fig. 4a, Eq. 2, $p < 0.05$, $R^2 = 0.96$). The only consistent, long-term dynamics in the forest occurred in the *Cassinia longifolia* - *Daviesia mimosoides* shrub layer. Shrubs regained their height by approximately 20 years after fire (Fig. 4b, Eq. 3, $p < 0.05$, $R^2 = 0.94$), thinning in a steep linear trend. By 30 years post-fire, plants were approximately 3 times more widely spaced compared to early-disturbance stands (Fig. 4c, Eq. 4, $p < 0.05$, $R^2 = 0.74$).

$$NS\ height = 0.277(1 - e^{-0.745age}) \qquad \text{Eq. 2}$$

$$shrub\ height = 0.912(1 - e^{-0.200age}) \qquad \text{Eq. 3}$$

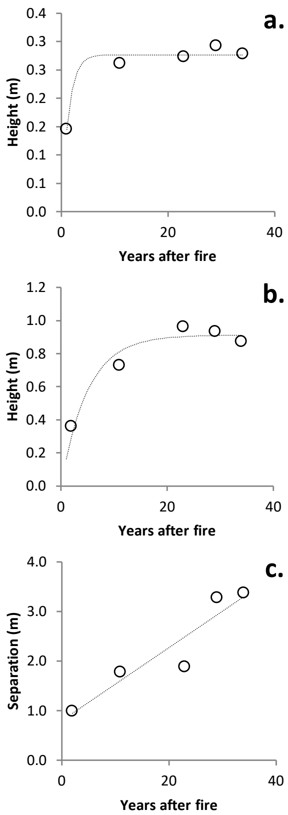


Figure 4 | Measured dynamics for a) height of grasses, b) height of shrubs, and c) separation between shrubs. Dotted lines represent equations 2 to 4, respectively.

Table 2 | Values and allometric ratios. Values used for the forest growth model.

Parameter	**Value**
Near surface base	0m
Separation between near-surface	1.10m
Midstorey height	3.32m
Separation between midstorey	6.85m
Canopy height	12.67m
Separation between trees	9.96m
Allometric values (proportion of plant heights)	
Near surface width	1.64
Shrub base height	0.37
Shrub width	0.65
Midstorey base height	0.52
Midstorey width	0.51
Canopy base height	0.5
Canopy widths	0.41

$$shrub\ sep = 0.064age + 0.919 \quad \text{Eq.4}$$

Along with these equations, the model was parameterised with mean values and allometric relationships measured from the data (Table 2).

Severity effects

The shrub *Daviesia mimosoides* is known to be strongly stimulated to germinate by fire[32]. Although that study did not determine whether the primary stimulant was heat or smoke, legumes are typically heat stimulated[33]. Other work[34] has also identified a weakly significant effect of heating on the germination of *Cassinia longifolia*, which also has a soil-stored seed-bank.

Fire weather and slope made only very small differences to soil heating for these scenarios, however, higher sand content in the soils led to slightly greater heat penetration (Table 3). Legume seed dormancy breaks at temperatures above 60-80°C and seed death tends to occur at temperatures of 100°C and greater[33], therefore, the modelled differences were too small and the zone of seed survival and germination will be similar across all soils and treatments.

Table 3 | Soil heating. Maximum temperatures reached in the top two centimetres of soil.

		Max temperature (°C) per depth	
Texture	**Treatment**	**1cm**	**2cm**
Loam	*Mild*	266	67
	V. high	266	69
Sandy loam	*Mild*	273	70
	V. high	274	73
Clay loam	*Mild*	261	65
	V. high	261	67

Modelled behaviour

Modelled fire behaviour (Fig. 5) consisted of predominantly low, slow-spreading flames with patchy torching (passive crown fire).

Median flame heights grew rapidly larger as forests aged to approximately 10 years, then remained relatively constant. Flame height variability was however largest in the first 20 years, so that large flames became increasingly less likely as forests aged beyond 10 years (Fig. 5a).

Rates of spread increased as forests aged for the duration of the modelled ages, with the rate of increase slowing in older forests (Fig. 5b). This was largely irrelevant to containment success however as rates were always low.

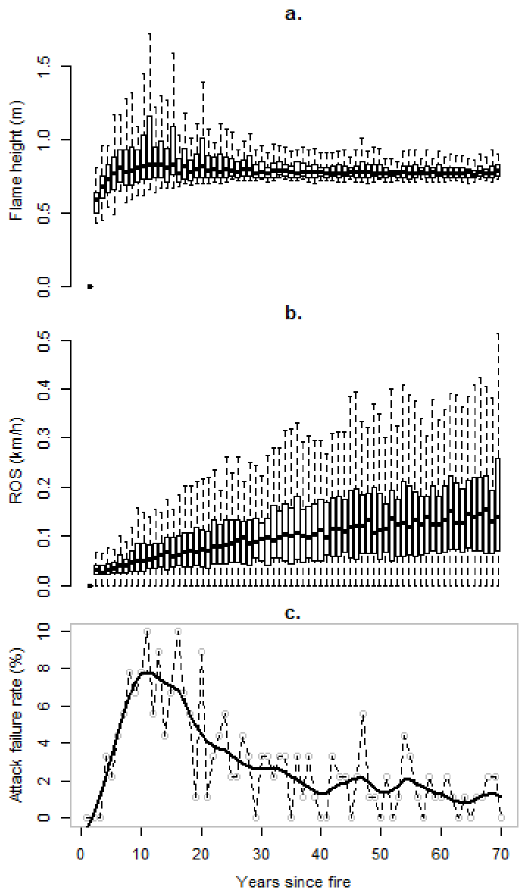


Figure 5 | Modelled flammability dynamics. Modelled for southern tablelands dry sclerophyll forest from 1 to 70 years of age, using summer 2018/19 weather. Plots are **a.** flame height, **b.** fire rate of spread, and **c.** percentage of the summer where direct attack is likely to fail. Boxplots show standard interquartile ranges; whiskers extend to 1.5 standard deviations.

When these factors were considered together to find the likelihood of direct attack fail, a humped distribution resulted, where fires were increasingly difficult to contain through direct attack up until an age of approximately 10 years, then increasingly easy to contain after this age (Fig. 5c).

Risk assessment

Likelihood

FR_{ps} could be represented by Equation 5 (R^2 = 0.59). This gives a feedback strength of 2.2, with a post-fire recovery period of 28 years.

$$FR_{ps} = \frac{0.0728age^{1.6}}{(1+(0.07age)^{2.6})^{1.4}} \qquad \text{Eq.5}$$

Fire likelihood derived from this function was highest for the 20-year burning cycle, and lowest for the 20-year fire exclusion treatment (Table 4).

Table 4 | Fire likelihood. For each treatment scenario, values are given first for the burn treatment, then for the equivalent no-burn treatment.

Scenario	Age range	FR_{ps}	Frequency	Likelihood
5 years	0 - 5	0.44	113	8.85×10^{-3}
	50 - 55	0.34	148	6.76×10^{-3}
10 years	0 - 10	0.97	51	1.96×10^{-2}
	50 - 60	0.31	161	6.21×10^{-3}
20 years	0 – 20	1.40	36	2.78×10^{-2}
	50 - 70	0.27	187	5.35×10^{-3}

Consequence

Weather conditions for the mild and very high fire danger conditions were taken from April 19th 2018, and February 11th 2019, respectively. Modelled fire behaviour (Appendix I) indicated that some level of canopy scorch was always likely, but complete scorch was limited to approximately 10% of the area except in old

Table 5 | Fire consequence. Direct threat from fire to koalas, modelled for mild and very high fire conditions. Values indicate the percentage of each burn expected to cause the impact.

	Age	*2nd deg.*	*3rd deg.*	*Death*
Mild	5	20%	5%	0%
	10	10%	5%	5%
	20	5%	0%	0%
	50	5%	0%	0%
Very high	5	40%	25%	20%
	10	40%	20%	10%
	20	55%	15%	5%
	50	80%	15%	0%

forests burnt under very high conditions. Crown fires were rare, and only occurred under milder conditions and not on steep slopes. Shrubs and midstorey were scorched in all scenarios, but only consumed in small areas.

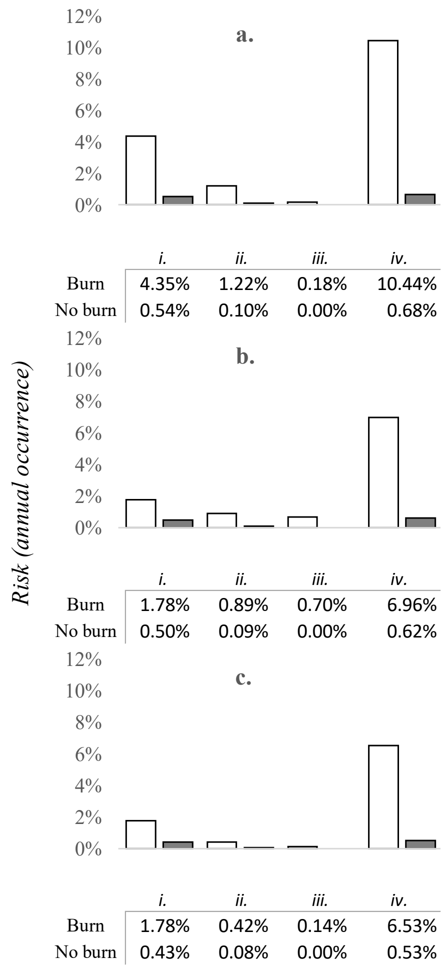
Modelling of the impact of fire on koalas (Table 5) indicated that direct mortality from the fire front is unexpected under mild conditions, but can be expected for up to 20% of the burn area during very high fire conditions in 5-year-old forests. As forests aged, the percentage of each burn that caused death or third-degree burns decreased, so that in mild conditions, such burns were only likely in 5 or 10-year-old forests.

Second-degree burns had a more complex relationship with forest age, becoming less likely in older forests burnt under mild conditions, but more likely in older forests burnt under very high fire danger conditions.

Risk

Modelling indicated that the risk to koalas and important habitat features such as shrub cover and canopy foliage was larger in the burning treatments than in the fire exclusion treatments (Fig. 6, Appendix I Table A1). In all measures of risk, fire exclusion was the most effective means of risk reduction.

Greater burn frequencies produced greater risks of 2nd and 3rd degree burns to koalas, and increased risk of shrub consumption after fire. The greatest risk of direct mortality however occurred if sites were burn on a 10-year cycle, and the risk of crown scorch loss was greatest in longer burn cycles.



a.	i.	ii.	iii.	iv.
Burn	4.35%	1.22%	0.18%	10.44%
No burn	0.54%	0.10%	0.00%	0.68%

b.	i.	ii.	iii.	iv.
Burn	1.78%	0.89%	0.70%	6.96%
No burn	0.50%	0.09%	0.00%	0.62%

c.	i.	ii.	iii.	iv.
Burn	1.78%	0.42%	0.14%	6.53%
No burn	0.43%	0.08%	0.00%	0.53%

Figure 6 | Comparative risk analysis. Graphs and associated tables give the annual point likelihood of 2nd degree burns (i.), 3rd degree burns (ii.), death (iii.), and >50% crown scorch (iv.). Scenarios are for five-yearly burn rotations (**a.**), 10-year rotations (**b**), and 20-year rotations (**c**). Clear columns show the risk when prescribed burns are used, and dark columns show the risk for the equivalent no-burn period.

Discussion and recommendations

In all scenarios, fire exclusion was the most effective technique for risk reduction, both for fire control and for koala protection.

The capacity for controlling wildfires was greater when there was no intentional introduction of fire, as fire produced dense shrub recruitment, creating a more flammable landscape (Fig. 7). Moderate frequency fires (10 – 20 years) increased this risk the most, as they maintained the forest in its most flammable state.

The relationship of burn frequency to koala risk differed slightly due to the complexities of heat transfer. Risk to koalas increased dramatically when prescribed burns were implemented, as the increased likelihood of wildfire was magnified by the risk from the burns themselves. Prescribed burning programs increased the risk of 2nd degree burns to koalas by 360% to 810%, 3rd degree burns by 520% to 1200%, and created the likelihood of direct mortality where it would not have existed if the forest was left in its long-unburnt state. The likelihood of scorching more than 50% of the canopy was increased by 1120% to 1550%. In all cases, the most damaging treatment was the most frequent (5-year) burn rotation, due to the risk posed by prescribed burns themselves.

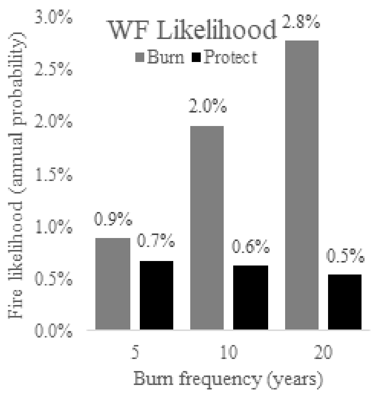


Figure 7 | Wildfire likelihood. From Table 4. Grey columns show the annual probability of a wildfire impacting a point under the three burning frequencies, and black columns show the corresponding probability if no fire is introduced.

A number of factors affect the consequence to koalas. The typically low canopy in this forest places them in a position that is vulnerable to fire, regardless of the intensity. This conflicts with the popular notion that wildfire causes damage but prescribed fire is beneficial. The sparse shrub cover limits flame dimensions and ladder fuels so that crown fires are rare, permitting little difference in flame dimensions between fires burning in a wide range of conditions. Even greater thinning of the shrub cover in older forests however results in increased wind access to surface fires, so that these spread faster as forests age. The combined result of these factors is that:

1. All fires pose a threat to koalas. Increasing fire frequency in any way increases the likelihood of habitat damage, and koala injury or death.
2. The faster-spreading fire front in older forests passes slightly faster beneath trees, so that, in combination with the smaller flames resulting from the sparser understorey, the consequence to koalas is lower.

Severity effects

Based on this analysis of measured vegetation dynamics, fires were 2.2 times more difficult to control for 28 years after a prescribed burn. As expected, this feedback strength was slightly less than the average for all fires, which was a 2.6-fold increase for 19 years following fire relative to the following 31 years (Fig. 8). The 10-year peak in flame height and crown fire likelihood (Fig. 5) is also very similar to post-fire trends in dry forests across eastern Australia, as is the limitation of crown fire to flat ground rather than steep slopes[35] (Appendix I, table A1).

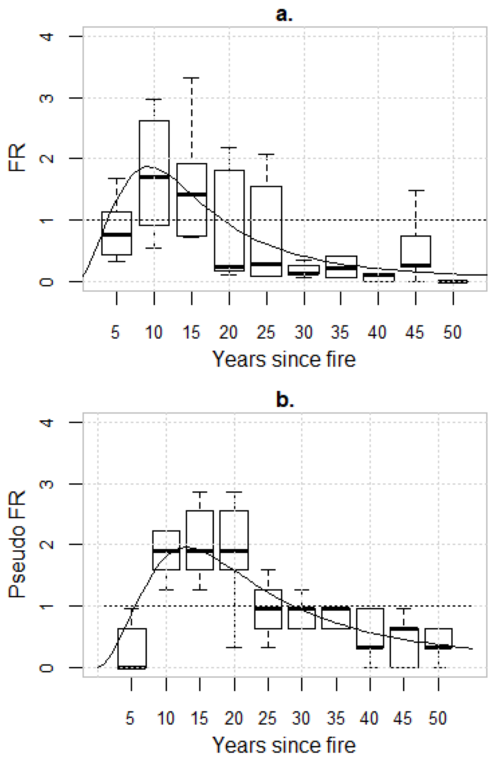


Figure 8 | Flammability ratios. **a.** Measured FR for forests recovering from fires of all severities (empirically measured in Zylstra 2018), **b.** modelled FR_{ps} for forest recovering from fires of low severity. Box plots show standard interquartile ranges; whiskers extend to 1.5 standard deviations.

As the difference in soil heating due to fire severity had little influence on shrub seed germination, it is likely that the greater feedback strength resulting from high severity fire relates to canopy loss itself. There are two mechanisms by which this may operate.

Firstly, canopy cover provides *overstorey shelter*[2], where un-ignited foliage that is above a spreading fire acts to slow the rate of spread by slowing wind speeds, and shades litter fuels, reducing the rates of drying[36]. Secondly, loss of canopy cover stimulates the growth of shrubs by allowing greater light penetration[37]. Higher severity fires therefore create more fuels close to the ground, while removing sheltering vegetation that would otherwise dampen fire spread.

Recommendations

As noted earlier, this study complements the spatial analysis conducted by Parkins *et al*[1], which finds locations for hazard reduction treatments that will most effectively reduce the impact of fire on the koala population of the study area.

The term "hazard reduction" is commonly understood to imply the deliberate *introduction* of fire, however, the NSW Rural Fires Act[38] defines bushfire hazard reduction work as:

> *"The controlled application of **appropriate fire regimes** or other means for the reduction or modification of available fuels within a predetermined area to mitigate against the spread of a bush fire."*

This study demonstrates that, consistent with existing empirical studies, the introduction of fire is not an appropriate fire regime for the purpose, and therefore does not constitute hazard reduction in this forest. Due to the pronounced opening of the shrub layer as these forests age, the appropriate fire regime is to exclude fire.

While the greatest risk reduction is likely to be achieved by widespread fire exclusion, Parkins *et al* demonstrate that treatments will have more value in some areas than others as they will intercept likely fire paths. This gives rise to two recommendations.

1. Unless values other than hazard reduction and risk reduction to koalas necessitate it, fire should not be intentionally introduced to the study area.

2. Rapid fire suppression should be prioritised for the study area. To assist with this, fire authorities should consider designating as Strategic Fire Advantage Zones those areas identified by Parkins *et al* as having strategic value due to their location. The fuel treatment for these areas would be aggressive fire exclusion.

Limitations

These findings contain some important limitations. Vegetation dynamics were measured in forests recovering from low-severity fires, but high severity events are expected to promote stronger feedbacks. Given that canopy loss becomes increasingly likely as the frequency of prescribed fire increases, this study may under-estimate the increases in risk resulting from repeated prescribed burns. In addition, risk to koalas is also affected by habitat changes, predator-prey interactions resulting from vegetation change, movement of koalas in relation to weather events, and post-fire burns due to smouldering tree trunks. These factors have not been quantified, however, as most act to increase the risk, the findings of this report should be treated as conservative.

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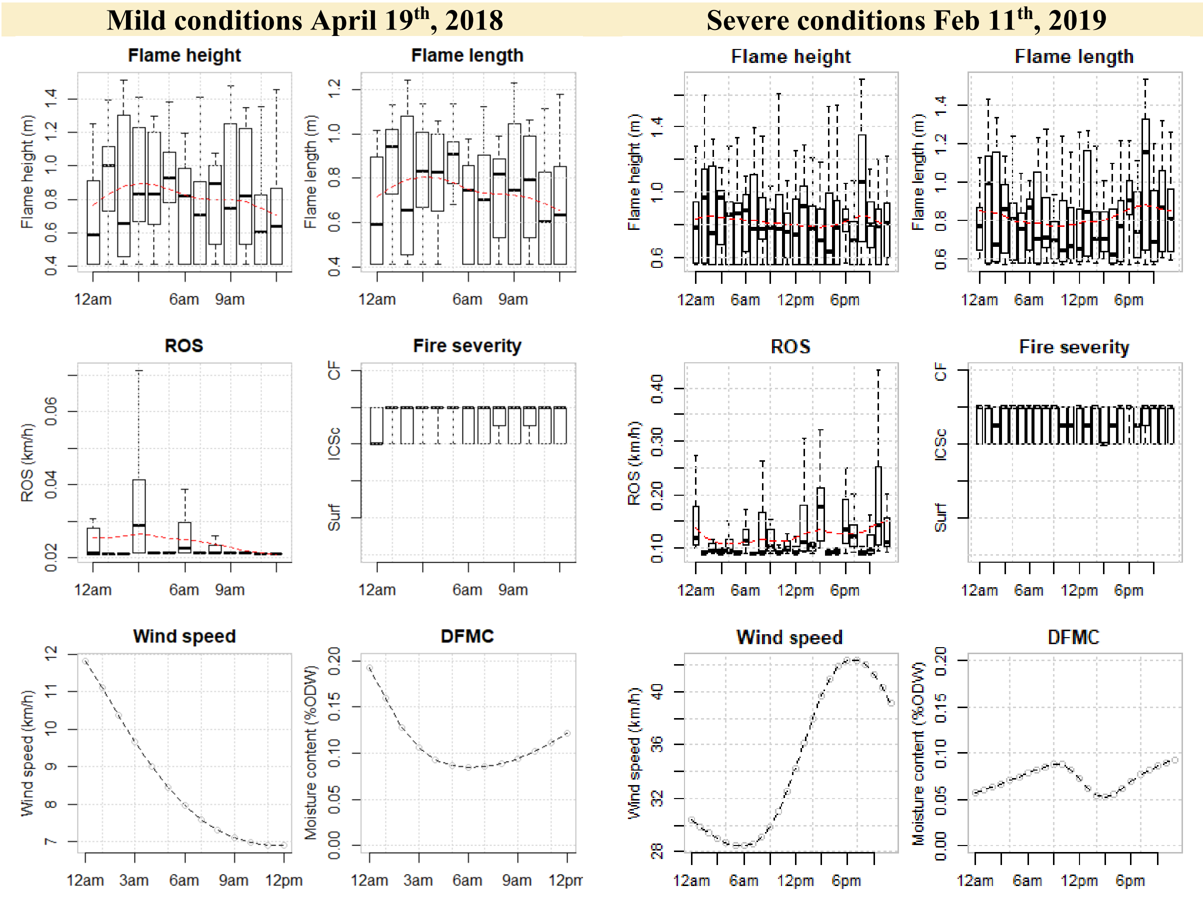
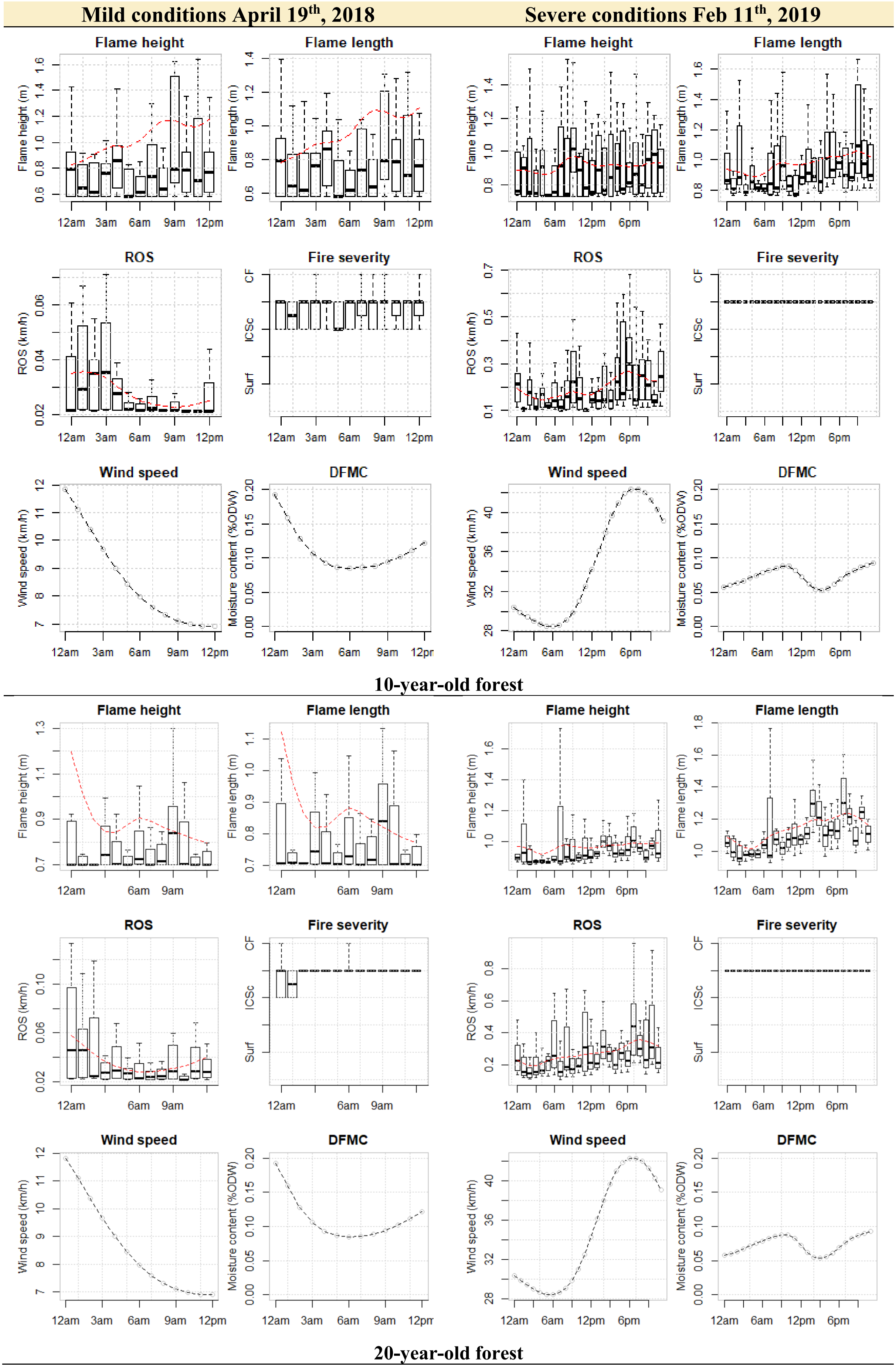
APPENDIX I. Modelled fire behaviour for scenarios

Modelled fire behaviour and weather conditions under prescribed and wildfire conditions for different forest age classes. Fire severity categories are: Surf - little to no plant impact, USc – understorey scorch, lCSc – light crown scorch, CSc – at least 50% crown scorch, CF – at least 50% crown consumption. Boxplots show standard interquartile ranges; whiskers extend to 1.5 standard deviations.



5-year-old forest


Mild conditions April 19th, 2018
Severe conditions Feb 11th, 2019
Flame height
Flame length
Flame height
Flame length
Flame height (m)
Flame length (m)
ROS
Fire severity
ROS
Fire severity
ROS (km/h)
CF
ICSc
Surf
Wind speed
DFMC
Wind speed
DFMC
Wind speed (km/h)
Moisture content (%ODW)
12am
3am
6am
9am
12pm
10-year-old forest
Flame height
Flame length
Flame height
Flame length
ROS
Fire severity
ROS
Fire severity
Wind speed
DFMC
Wind speed
DFMC
20-year-old forest

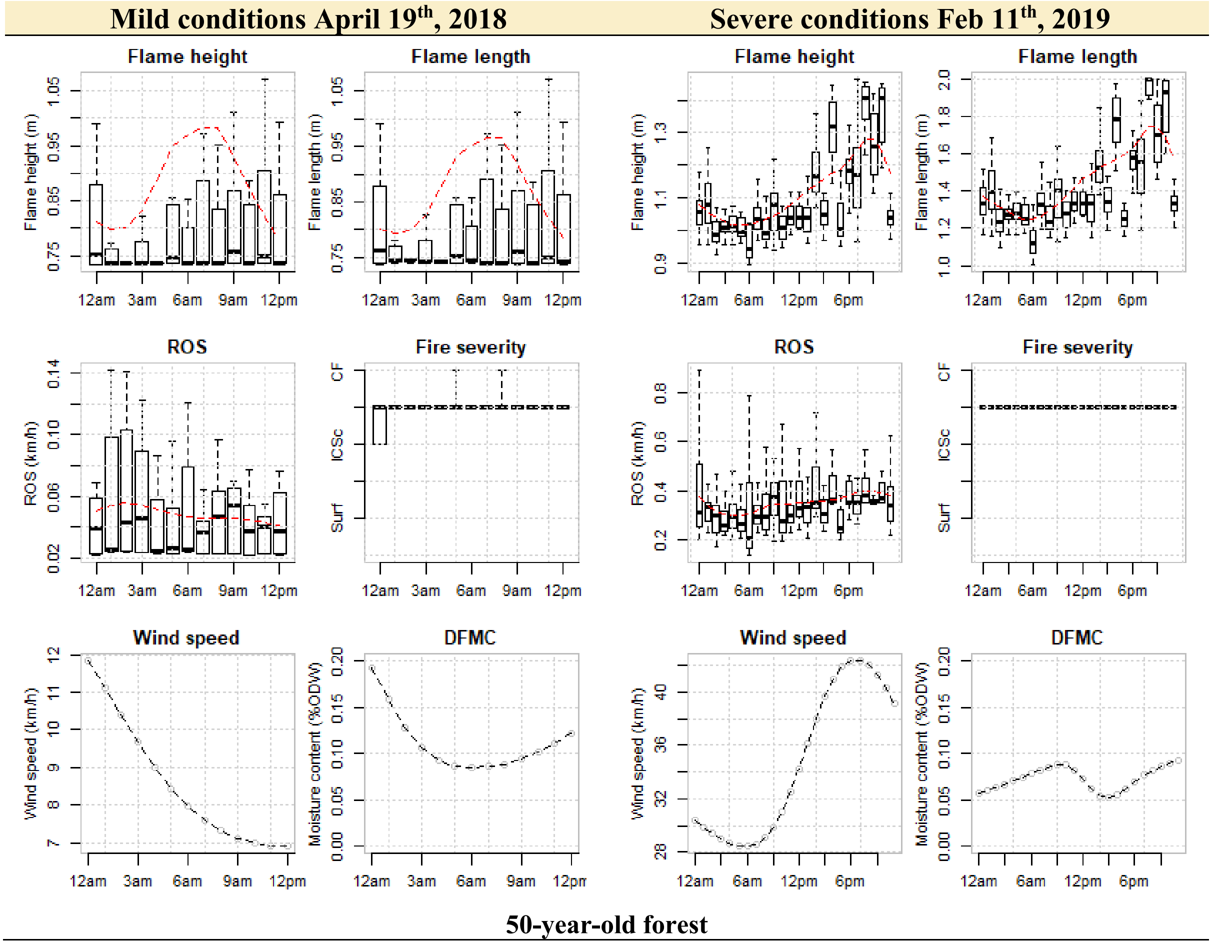

Mild conditions April 19th, 2018
Severe conditions Feb 11th, 2019
Flame height
Flame length
ROS
Fire severity
Wind speed
DFMC
Flame height (m)
Flame length (m)
ROS (km/h)
Wind speed (km/h)
Moisture content (%ODW)
CF
ICSc
Surf
12am
3am
6am
9am
12pm
6pm
50-year-old forest

Table A1 | Percentiles of fire behaviour.

Age and conditions	Percentile	Flame height (m)	Flame length (m)	ROS (km/h)	Shrub Scorch (%)	Shrub Consumption (%)	Midstorey Scorch (%)	Midstorey Consumption (%)	Canopy Scorch (%)	Canopy Consumption (%)
5 years, mild, 0º slope	0%	0.4	0.4	0.02	100	0	44	0	15	0
	5%	0.4	0.4	0.02	100	0	49	0	18	0
	25%	0.4	0.4	0.02	100	0	56	0	23	0
	50%	0.8	0.8	0.02	100	0	100	0	81	0
	75%	1.1	1	0.02	100	100	100	0	100	0
	95%	1.4	1.1	0.04	100	100	100	0	100	0
	100%	1.5	1.2	0.07	100	100	100	0	100	0
5 years, very high, 20º slope	0%	0.6	0.6	0.09	100	0	76	0	36	0
	5%	0.6	0.6	0.09	100	0	82	0	40	0
	25%	0.6	0.6	0.09	100	0	87	0	43	0
	50%	0.8	0.8	0.1	100	0	100	0	63	0
	75%	1	0.9	0.13	100	99	100	0	92	0
	95%	1.3	1.3	0.24	100	100	100	0	100	0
	100%	1.7	2.4	0.49	100	100	100	9	100	0
10 years, mild, 0º slope	0%	0.6	0.6	0.02	100	0	72	0	33	0
	5%	0.6	0.6	0.02	100	0	76	0	36	0
	25%	0.6	0.6	0.02	100	0	89	0	44	0
	50%	0.7	0.7	0.02	100	0	100	0	72	0
	75%	0.9	0.9	0.03	100	0	100	0	97	0
	95%	1.6	1.3	0.05	100	100	100	0	100	0
	100%	13.2	12	0.12	100	100	100	100	100	92
10 years, very high, 20º slope	0%	0.7	0.8	0.09	100	0	100	0	58	0
	5%	0.7	0.8	0.1	100	0	100	0	62	0
	25%	0.7	0.8	0.12	100	0	100	0	65	0
	50%	0.8	0.9	0.15	100	0	100	0	70	0
	75%	1	1	0.24	100	0	100	0	86	0
	95%	1.3	1.5	0.43	100	100	100	0	100	0
	100%	2.1	3.1	0.68	100	100	100	12	100	0
20 years, mild, 0º slope	0%	0.7	0.7	0.02	100	0	92	0	47	0
	5%	0.7	0.7	0.02	100	0	96	0	49	0
	25%	0.7	0.7	0.02	100	0	100	0	56	0
	50%	0.7	0.7	0.03	100	0	100	0	60	0
	75%	0.8	0.8	0.04	100	0	100	0	86	0
	95%	1.5	1.2	0.09	100	100	100	0	100	0
	100%	10.8	9.7	0.16	100	100	100	100	100	71

20 years, very high, 20º slope	0%	0.9	0.9	0.11	100	0	100	0	76	0
	5%	0.9	1	0.13	100	0	100	0	80	0
	25%	0.9	1	0.17	100	0	100	0	84	0
	50%	0.9	1.1	0.23	100	0	100	0	88	0
	75%	1	1.2	0.31	100	0	100	0	96	0
	95%	1.3	1.5	0.58	100	100	100	0	100	0
	100%	2.2	3.6	0.96	100	100	100	24	100	0
50 years, mild, 0º slope	0%	0.7	0.7	0.02	100	0	98	0	50	0
	5%	0.7	0.7	0.02	100	0	100	0	53	0
	25%	0.7	0.7	0.02	100	0	100	0	60	0
	50%	0.7	0.7	0.04	100	0	100	0	65	0
	75%	0.8	0.8	0.06	100	0	100	0	86	0
	95%	1	1	0.11	100	0	100	0	100	0
	100%	12.4	11.2	0.26	100	100	100	100	100	87
50 years, very high, 20º slope	0%	0.9	1	0.13	100	0	100	0	86	0
	5%	1	1.2	0.21	100	0	100	0	93	0
	25%	1	1.3	0.26	100	0	100	0	100	0
	50%	1.1	1.4	0.34	100	0	100	0	100	0
	75%	1.2	1.6	0.39	100	0	100	0	100	0
	95%	1.4	2	0.58	100	0	100	0	100	0
	100%	3.7	8.1	1.05	100	100	100	100	100	43