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Recruitment and mortality of the fire sensitive *Eucalyptus fraxinoides* after the 2019-20 wildfires, Monga National Park, southern New South Wales

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Abstract: Wildfires are prevalent across Australian landscapes; this is evident in the number of fire-adapted plant species in Australian ecosystems, including most eucalypts. In eastern Australia, there are fewer than 10 fire sensitive eucalypt species including *Eucalyptus fraxinoides*, whereby 100% leaf scorch results in mortality. Stands of *Eucalyptus fraxinoides* were burnt in the recent 2019-20 bushfires, which significantly affected Monga National Park in southern New South Wales. There are no post-fire studies on this species, and our aim was to determine recruitment and mortality rates, one year after severe wildfire, by measuring stem diameter (DBH), sapling cover and abundance, and mortality rates of adult trees across low, moderate and extreme fire severities. Bayesian modelling was applied to determine mortality related to severity, where results showed strong effects of fire severity on recruitment and mortality.

Strong effects of fire severity on the likelihood of mortality were evident. High severity fire was shown to cause 100% mortality of stems, regardless of stem size. The likelihood of mortality in low and moderate fire severity decreased with increasing stem size. Sapling recruitment increased in density with increasing fire severity. High rates of recruitment following high severity fire and lower rates of mortality with increasing stem size in low severity fires, demonstrates this species resilience to fire.

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Introduction

Fire is widespread across Australia and is a key driver in shaping plant community assemblages (Bond & Midgley 2001; Bradstock 2008; Kubiak 2009); as such it is an integral part of Australian ecosystems (Jurskis 2005). Many species have evolved traits that enable persistence after fire disturbance (Pausas & Keeley 2014; Pausas 2015) and these traits vary in their expression under different fire regimes (Williams & Woinarski 1997). Gill (1975) defines adaptive traits in relation to fire as an aspect of the plant which facilitates its survival, either through enduring the fire (i.e. avoiding death) or through recruitment (i.e. persisting through new individuals). Post-fire environments provide optimal conditions for regeneration, as established plants are eradicated, providing space for new individuals (Bond & Van Wilgen 1996; Gill *et al.* 2002; McCaw 2015). This provides favourable conditions for successful recruitment through reduced competition and increased nutrient-rich soils from ash (Vivian *et al.* 2008; Booth 2017). However, varying gradients in fire severity causes variation in post-fire environments (Gill *et al.* 1981; Vivian *et al.* 2008).

Although most eucalypts species survive fire by resprouting, there are a few (less than 10 species in eastern Australia) that are fire-sensitive (Nicolle 2006), whereby 100% leaf scorch results in mortality (Gill *et al.* 1981), including *Eucalyptus delegatensis* (closely related to *Eucalyptus fraxinoides*) and *Eucalyptus oreades* which respond to fire through mortality of adult stems and mass regeneration (Gill 1997; Wardell-Johnston 2000; Glasby 1988). Vivian *et al.* (2008) found high rates of mortality of *Eucalyptus delegatensis* in high severity sites and lower in low severity. A similar effect was observed by Bowman *et al.* (2014) who found that a single fire caused death of adults, and a mass regeneration event followed. Thus, extreme fire sensitivity of adults is offset by high rates of recruitment. The ability for these fire-sensitive eucalypts to survive to sexual maturity is dependent on appropriate fire regimes (Glasby *et al.* 1987).

There is anecdotal evidence that *Eucalyptus fraxinoides* is fire sensitive and that the predicted increase in future fire regimes places this species at risk of population decline, but no formal fire studies have been conducted. The focus of the few studies on this species has been on soil and foliar content (Lambert & Turner 1983), seedling growth and competition experiments (Prober 1992) and generalised classifications of its surrounding habitat (Nicolle 2006). The aim of this study therefore was to determine the fire-resilience of *Eucalyptus fraxinoides* by examining the rates of recruitment and mortality across a range of low, moderate and extreme fire severity sites resulting from the 2019-20 bushfires in southern NSW.

Study Area – Monga National Park

Monga National Park (Monga NP) (35°37'29.4" S; 149°54'36.4" E), 300 km south-west of Sydney, New South Wales (NSW) (Fig. 1) is characterised by a temperate climate with distinct seasonal variation (OEH 2014). Monga NP has experienced many prescribed and wildfires in the last 50 years, with the most recent wildfire burning from December 2019 to February 2020 (*Clyde Mountain Fire* -NSW Rural Fire Service 2020). This fire was part of a much larger fire, named the *Currowan Fire*, which burnt 315,643 ha. Within this total area, 98% (26,573 ha) of Monga NP was burnt (NSW Rural Fire Service 2020). For more detail on the study area see Mikac *et al.* (2021).

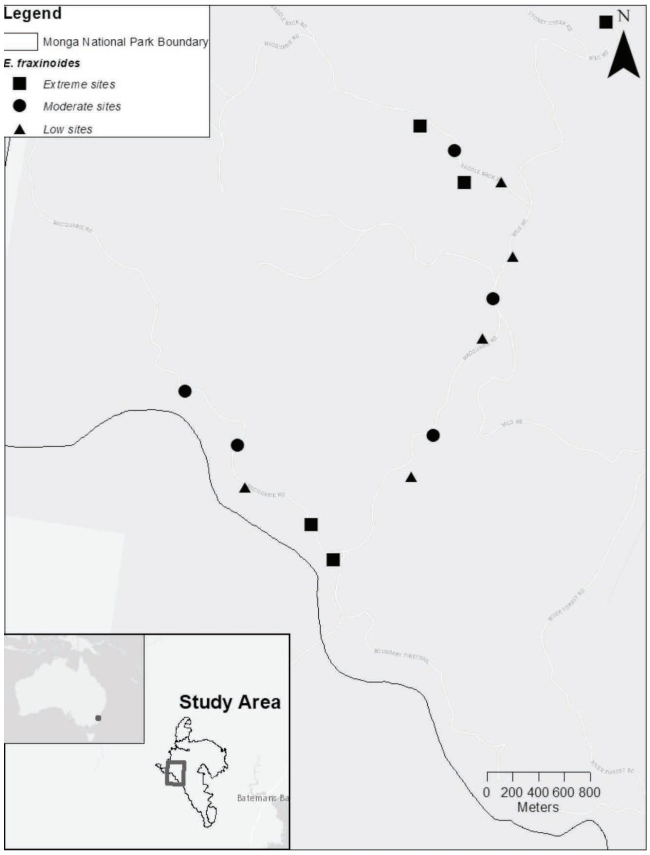

Figure 1. Location of *Eucalyptus fraxinoides* study sites, within Monga National Park, New South Wales, Australia (35°37'29.4"S 149°54'36.4"E). Low fire severity = triangle, moderate fire severity = circle, extreme fire severity = square.

Methods

Recruitment and mortality of *Eucalyptus fraxinoides* under different fire severity regimes (low, moderate and extreme) were examined at a range of sites, though severity did not account for antecedent fires. All data was collected one year post-fire. Tree size was expressed as diameter at breast height (DBH), and eucalypt recruitment was assessed using foliar cover and eucalypt seedling abundance across sites. Trees less than 50 cm tall were regarded as post-fire saplings. Foliar cover, a function of both plant abundance and size (Morrison *et al.* 1995), is defined as the "percentage of ground covered by the vertical projection of plants" (Anderson 1986).

Field Methods

Recruitment and mortality were measured in 15 replicate 20 x 50 m (1000 m^2) plots, with recruitment being measured within a 20 x 20 m (400 m^2) plot inside the 1000 m^2 (Fig. 2). The decision to survey recruitment and mortality in different size plots was based on the recommendations of varying heights of plants (Silversteen 2009); the standard 20 x 20 m plot enabled comparability with published datasets. Three fire severity categories were measured: low (burnt understory with unburnt canopy), moderate (burnt understory and partial canopy scorch) and extreme severity (full canopy consumption) (NSW Rural Fire Service 2020). Recruitment abundance was counted in 10, 1 x 1 m^2 subplots randomly stratified within the 400 m^2 plots. The average of these subplots was then multiplied by 400. Foliar cover was assessed by visual estimations of the percentage of cover within the 10, 1 x 1 m^2 subplots. The average was multiplied by 400 to get an estimation of the total area occupied. In the 1000 m^2 plots, all adult *Eucalyptus fraxinoides* trees were recorded as alive or dead and DBH was recorded.

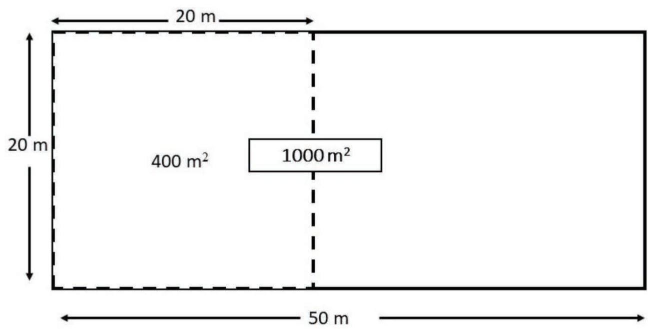

Figure 2. Example of the plot layout used to collect data, with recruitment rates measured within the 400 m^2 plot and adult mortality surveyed within the 1000 m^2 plots.

Statistical Analysis

Significant differences among fire severity groups in eucalypt recruitment, foliar cover and sapling abundance were analysed using a one-way ANOVA. Foliar cover and abundance were analysed separately, against different levels of fire severity. Visual examination of residual distributions confirmed data normality and a Cochran's C test was undertaken to confirm heterogeneity of variances. Post-hoc Tukey's Honestly Significant Difference (HSD) test was conducted to test for significant differences between categories within factors. The statistical software JMP® (Version *15*. SAS Institute Inc., Cary, NC, 1989-2019) was used.

A Bayesian modelling approach was implemented to quantify the probability of mortality in *Eucalyptus fraxinoides* due to fire severity, and the degree to which mortality is moderated by tree size. DBH was fitted as an additive term to account for effect of tree size on canopy topkill response (Denham *et al.* 2016). Site was added as a random effect to account for the effect of variability between sites:

(1) P mortality ~ fire severity + DBH + (site|1)

Mortality across three fire severity categories (low, moderate and extreme) was modelled as a Bernoulli-distributed variable and four chains consisting of 5000 model iterations were sampled. The models were visually checked using graphical summaries of the density and trace plots. The between and in chain estimates for model parameters were checked using the r-hat convergence diagnostic (Gelman & Rubin 1992). A matrix of posterior samples from the models was used to generate predictions of probabilities for the treatment groups. Then the matrix of posterior samples was used to calculate distributions of differences between treatment groups of interest (Quinn & Keough 2002). Highest posterior density intervals (HPDI) were calculated to show the central 50% of model predictions and the upper/lower 95% bounds of model predictions (i.e. 'credible intervals'). The statistical software R version 1.2.5033 was used for analysis, using the 'brms' package (Bürkner 2017, R Core Team 2019).

Results

Post-fire sapling recruitment

Fire severity significantly increased post-fire sapling cover and abundance in *Eucalyptus fraxinoides.* Extreme fire severity had nearly twice the average foliar cover of moderate severity sites, and nearly ten times more than low severity ($F_{2,14}$=47.86, p< 0.0001; Fig. 3a). Extreme fire severity also resulted in a significantly greater abundance of post-fire sapling recruitment than moderate and low fire severity ($F_{2,14}$= 15.36, p <0.0005; Fig 3b).

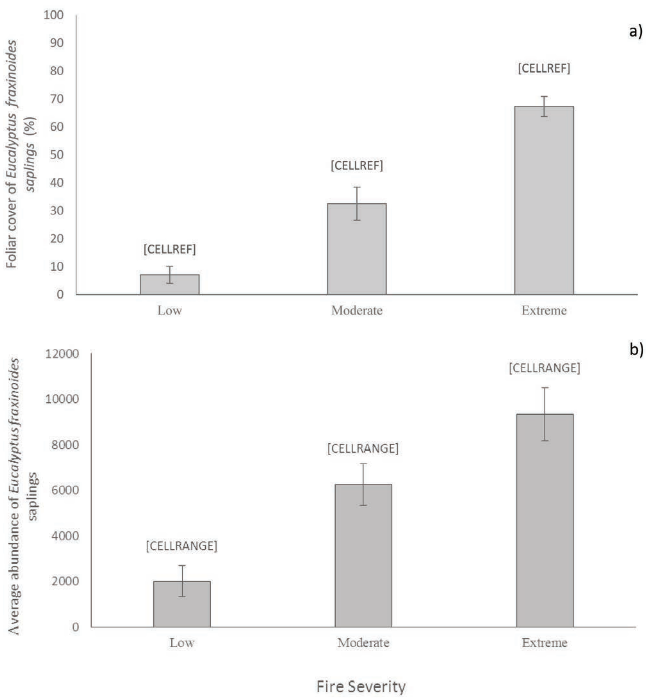

Figure 3. The mean (±SE) of eucalypt saplings across different fire severities, a) the average foliar cover of *Eucalyptus fraxinoides* saplings (*n* = 15), and b) the relative abundance of *Eucalyptus fraxinoides* saplings (*n* = 15). Bars in graph not connected by the same letter represents statistical difference (p < 0.05), according to Tukey's HSD within each level of fire severity.

Mortality of Eucalyptus fraxinoides

Of 405 *Eucalyptus fraxinoides* trees measured, 75% (304) had been killed by the fire. The pre-fire tree density ranged from 12-58 per 1000 m^2 site (average 27± SE 3.34) across all sites, DBH ranged from 9.6 – 136.9 cm (average 42.5 ± 23.1 cm). Trees experiencing extreme fire severity had a 100% probability of mortality, regardless of DBH (Fig. 4). Mortality was less likely to occur in trees found in low fire severity sites compared to moderate severity sites, however, this decreased with tree size. In low fire severity sites, there was a very low likelihood of mortality for large trees above 75 cm DBH (Fig. 4). There was a minor increase in the probability of mortality in moderate fire severity sites compared to trees experiencing low fire severity (Fig. 4). Overall, increasing fire severity and decreasing stem size led to an increase in the likelihood of mortality. Only 12 trees exhibited epicormic growth, less than 3% of trees recorded (Fig. 5).

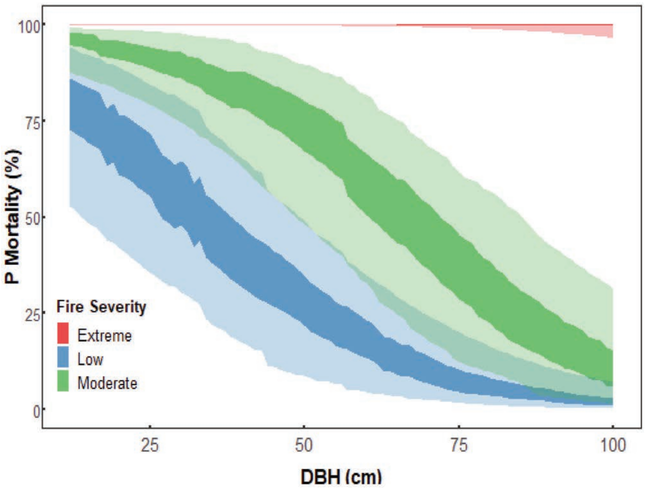

Figure 4. The effect of fire severity (low = blue; moderate = green; extreme = red) and DBH (x-axis) on the probability of mortality for *Eucalyptus fraxinoides* trees 10-100 cm DBH, within Monga National Park. Canopy unaffected represented by low fire severity, canopy partially affected represented by moderate fire severity and canopy entirely consumed represented by extreme fire severity. Darker coloured ribbons represent 50% credible intervals and lighter shaded ribbons represent 95% credible intervals.

Figure 5. *Eucalyptus fraxinoides* trees in moderate severity sites 10 months post-fire, exhibiting epicormic resprouting on trunk and branches, Monga National Park, New South Wales.

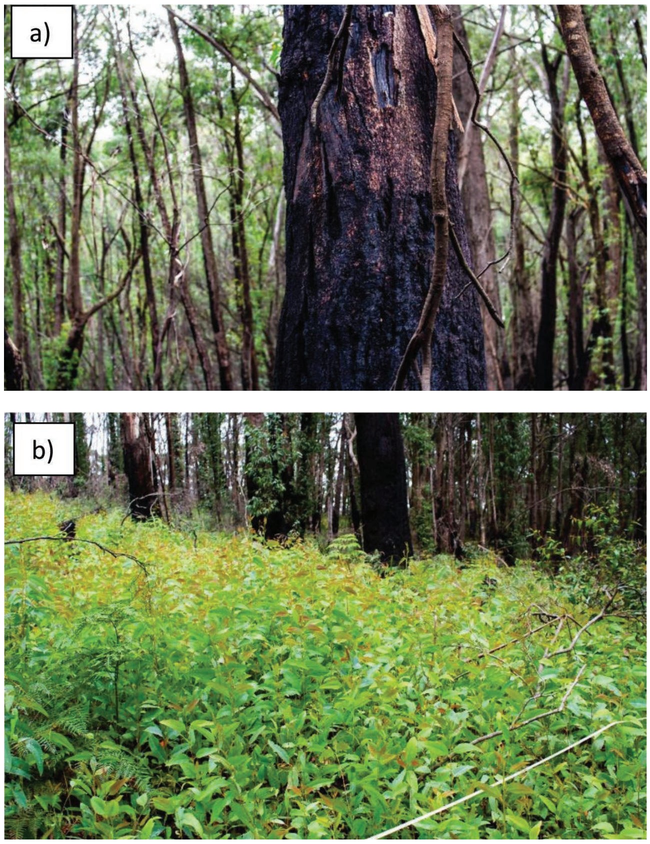

Figure 6. *Eucalyptus fraxinoides* trees in Monga NP, NSW, Australia, a) photo of *Eucalyptus fraxinoides* thick stocking of bark on the lower part of the trunk, b) seedlings in an extreme fire severity plot.

Discussion

Recruitment

Fire-sensitive obligate seeders killed by 100% leaf scorch, such as *Eucalyptus fraxinoides,* respond with sapling cohorts; in the absence of fire, recruitment is very rare (Nicolle 2006). For close relative fire-sensitive *Eucalyptus delegatensis*, Vivian *et al.* (2008) found that sapling density was significantly greater at higher severity sites. In *Eucalyptus fraxinoides* fire severity significantly increased post-fire sapling cover and abundance*,* the results highlighting the impacts of fire gradients for sensitive trees. High fire severity provides optimal conditions for recruitment (Bowman & Kirkpatrick 1986; Williams & Woinarski 1997; Bailey *et al.* 2012), and in this study, sites which were burnt at high fire severity had significantly higher rates of eucalypt recruitment. The abundance of saplings was significantly lower in low severity sites, but sapling abundance in extreme sites was not significantly different to moderate severity sites, though a significant difference in foliar cover between extreme and moderate sites was observed. This may be due to intraspecific competition between the high numbers of saplings in extreme sites. Abundance may have been higher initially in the extreme severity sites, but better-established individuals may have soon outcompeted others. Glasby *et al.* (1987) found that high recruitment rates in

Eucalyptus oreades caused strong intraspecific competition and eventually led to a varied size-class in even-aged stands. The supressed individuals die prematurely, but reach sexual maturity faster, ensuring seed stores are rapidly available (Glasby *et al.* 1987). Bowman and Kirkpatrick (1986) found that for *Eucalyptus delegatensis,* adult trees suppressed sapling growth. The ability to reach sexual maturity faster may prove to be highly advantageous, however further research is needed to determine if *Eucalyptus fraxinoides* exhibits this ability. In this study it was evident that *Eucalyptus fraxinoides* saplings had higher sapling density when compared to other eucalypt saplings (*Eucalyptus sieberi, Eucalyptus fastigata*), but *Eucalyptus fraxinoides* dominated sites had been targeted specifically (Fig. 6b).

Mortality

For *Eucalyptus fraxinoides*, high severity burns caused 100% death, regardless of stem size, but a size class effect was observed for low and moderate severity burns. These results are consistent with fire sensitive *Eucalyptus delegatensis*, where high severity fire have caused high mortality rates (Bowman *et al.* 2014), lower rates of mortality were observed in lower severity sites (Vivian *et al.* 2008), and lower survival rates were observed in populations with higher proportions of smaller stems (*Eucalyptus delegatensis* subsp. *tasmaniensis*) (Rodriguez-Cubillo *et al.* (2020).

Possessing thick bark at the lower part of the trunk is adaptive in environments with surface or low intensity fires (Pausas 2015). Fire-sensitive *Eucalyptus regnans* has a thicker rough basal stocking restricted to the lower half of the stem (Cremer 1962). Mature *Eucalyptus fraxinoides* trees possess a thick stocking of bark on the lower trunk (Fig. 6a) and appear to be tolerant of low intensity fire to some extent, provided that individual trees are large enough, and canopies high enough to avoid scorch. Though not specifically investigated, a few *Eucalyptus fraxinoides* trees within moderate fire severity sites in Monga NP, exhibited some epicormic response on their branches (Fig. 5). This could indicate some capacity to resprout, but further studies are needed to establish whether these epicormic shoots assisted canopy re-establishment or subsequently perished. Waters *et al.* (2010) found that *Eucalyptus regnans* resprouted epicormically under some conditions.

Our results demonstrate the resilience of fire-sensitive *Eucalyptus fraxinoides* to fire, through high reproductive capacity, and ability to survive even moderate severity fire when stems are of substantial size. Further study on *Eucalyptus fraxinoides* fire ecology is warranted as predicted changes to fire regimes may potentially impact its abundance. Future research should incorporate bark thickness, and intraspecific and interspecific competition. The effect of bark thickness is a highly adaptive trait in eucalypts (Wesolowski *et al.* 2014; Nolan *et al.* 2020) and may explain the variation in tolerance at lower fire intensities; competition may impact the ability of saplings to establish. By incorporating information on canopy species abundance and overstorey shading, a more detailed understanding of *Eucalyptus fraxinoides* fire ecology may be established.

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