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Research article

Mechanical treatments and prescribed burning can reintroduce low-severity fire in southern Australian temperate sclerophyll forests

James M. Furlaud [a,b,*], Grant J. Williamson [a], David M.J.S. Bowman [a]

[a] School of Natural Sciences, University of Tasmania, Hobart, TAS, Australia
[b] CSIRO Environment, Private Bag 44, Winnellie, NT 0821, Australia

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ABSTRACT

The establishment of sustainable, low-intensity fire regimes is a pressing global challenge given escalating risk of wildfire driven by climate change. Globally, colonialism and industrialisation have disrupted traditional fire management, such as Indigenous patch burning and silvo-pastoral practices, leading to substantial build-up of fuel and increased fire risk. The disruption of fire regimes in southeastern Tasmania has led to dense even-aged regrowth in wet forests that are prone to crown fires, and dense *Allocasuarina*-dominated understoreys in dry forests that burn at high intensities.

Here, we investigated the effectiveness of several fire management interventions at reducing fire risk. These interventions involved prescribed burning or mechanical understorey removal techniques. We focused on wet and dry *Eucalyptus*-dominated sclerophyll forests on the slopes of kunanyi/Mt. Wellington in Hobart, Tasmania, Australia. We modelled potential fire behaviour in these treated wet and dry forests using fire behaviour equations based on measurements of fuel load, vegetation structure, understorey microclimate and regional meteorological data.

We found that (a) fuel treatments were effective in wet and dry forests in reducing fuel load, though each targeted different layers, (b) both mechanical treatments and prescribed burning resulted in slightly drier, and hence more fire prone understorey microclimate, and (c) all treatments reduced predicted subsequent fire severity by roughly 2–4 fold. Our results highlight the importance of reducing fuel loads, even though fuel treatments make forest microclimates drier, and hence fuel more flammable.

Our finding of the effectiveness of mechanical treatments in lowering fire risk enables managers to reduce fuels without the risk of uncontrolled fires and smoke pollution that is associated with prescribed burning. Understanding the economic and ecological costs and benefits of mechanic treatment compared to prescribed burning requires further research.

1. Introduction

Wildfire is one of the most predominant natural disturbances globally (Bowman et al., 2009), and disasters caused by wildfire frequently affect human communities in flammable biomes across the world (Bowman et al., 2017). Wildfire disasters, where extreme fires cause widespread loss of life or property, occur due to an interaction of flammable vegetation and densely populated human settlements (Lannom et al., 2014). While climate change seems to be driving a general increase in extreme fires (Di Virgilio et al., 2019; Jones et al., 2022), anthropogenic factors, such as disruption of fire regimes (defined as the characteristic frequency, severity, and seasonality of wildfire in an ecosystem; Bradstock et al., 2002; Keeley, 2009), and rapid growth of human settlements in the wildland-urban interface (WUI) are also substantial contributors to the increase in wildfire disasters (Bowman et al., 2020). In the context of the 17 UN Sustainable Development Goals, seven are related to wildfires, according to Martin (2019), highlighting the importance of planning wildfire risk mitigation in an ecologically sustainable fashion.

In western North American forests, the disruption of fire regimes has primarily occurred through the combined influence of the removal of Indigenous management followed by the active exclusion of wildfire, through deliberate fire suppression, from many forest ecosystems for over a century (Haugo et al., 2019; Spoon et al., 2015; Stephens and

* Corresponding author. School of Natural Sciences, University of Tasmania, Hobart, TAS, Australia.
E-mail address: james.furlaud@csiro.au (J.M. Furlaud).

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Table 1
Dominant understorey and canopy species along transects, along with forest structural variables, in untreated forests. Dominant understorey species were calculated as the percent of the total number of plants in the elevated layer. Dominant canopy species are based on the percent of total basal area. The summary of time since last fire at individual transects (mode, minimum, and maximum) was calculated from fire history maps from ES-GIS, Department of Natural Resources and Environment Tasmania 2022; https://www.thelist.tas.gov.au/app/content/data/geo-meta-data-record?detailRecordUID=b94d4388-995d-416a-9844-a39de2798bed) and communication with land managers.

Forest Type	Treatment	Dominant Elevated Layer Species	Dominant Canopy Species	Years Since Last Fire	Total Basal Area (trees >10 cm DBH)	Avg. Canopy Tree Height
Dry Sclerophyll	Shaded Fuel Break	*Allocasuarina* spp. *(18%)* *Dodonea viscosa (16%)* *Pimelia linifolia (15%)* *Bedfordia salicina (11%)*	*E. obliqua*	56 (10–56)	Canopy: 20 m^2 ha^{-1} Understorey: 1 m^2 ha^{-1}	8 m
	Mechanical Thin	*Dodonea viscosa (38%)* *Allocasuarina* spp. *(30%)* *Acacia dealbata (8%)*	*E. pulchella* *E. globulus*	25 (25–25)	Canopy: 6 m^2 ha^{-1} Understorey: 2 m^2 ha^{-1}	6 m
	Prescribed Burn	*Pultenaea juniperina (35%)* *Allocasuarina* spp. *(13%)* *Acacia melanoxylon (13%)* *Exocarpos cupressiformis (13%)*	*E. obliqua* *E. pulchella* *E. terminalis*	56 (13–56)	Canopy: 12 m^2 ha^{-1} Understorey: 1 m^2 ha^{-1}	7 m
Wet Sclerophyll	Shaded Fuel Break	*Acacia leprosa (19%)* *Coprosma quadrifida (17%)* *Olearia argophylla (11%)*	*E. obliqua* *E. regnans*	56 (41–56)	Canopy: 44 m^2 ha^{-1} Understorey: 3 m^2 ha^{-1}	15 m
	Prescribed Burning	*Coprosma quadrifida (17%)* *Nematolepis squamea (13%)* *Pittosporum bicolor (13%)* *Beyeria viscosa (13%)*	*E. obliqua* *E. delegatensis*	56 (22–56)	Canopy: 31 m^2 ha^{-1} Understorey: 2 m^2 ha^{-1}	14 m

Ruth, 2005; Swetnam, 1993). This has homogenised much of the landscape with dense, flammable trees that act as ladder fuels, increasing the risk of high-severity crown fire (Odion et al., 2014). In Mediterranean Europe, industrialisation has led to urban migration and abandonment of silvo-pastoral practices leading in turn to an increase in fuel loads and fire risk in surrounding rural landscapes (Moreira et al., 2011; Moreno et al., 2014). This is especially problematic in ecosystems with regimes of frequent, low-to-moderate severity fires, where dominant species such as *Pinus ponderosa* in North America and *Quercus suber* and *Pinus pinaster* in Europe are adapted to low-severity surface fire (Allen et al., 2002; Fernandes et al., 2008; Francos et al., 2016). In the WUI this causes risk to life and property, along with degradation of biological and structural diversity (Perry et al., 2011). In Australian *Eucalyptus*-dominated sclerophyll forests, the removal of indigenous management through European colonisation, commencing in 1788, disrupted a legacy of 60,000 years of ecological management through the deliberate use of fire (Fletcher et al., 2021; Mariani et al., 2022).

Two examples of such disrupted fire regimes can be seen in the dry and wet sclerophyll forests of Tasmania, Australia's southernmost state. These forests are dominated by highly flammable species of *Eucalyptus*, which require fire as part of their life cycle and can survive fire through vigorous epicormic resprouting (Ashton, 1981; Collins, 2020; Furlaud, Prior, Williamson and Bowman, 2021a). Dry forest understoreys are regularly dry enough to burn (Nyman et al., 2015), and, being dominated by grasses and shrubs with slender, scleromorphic leaves, they are highly combustible (Tumino et al., 2019; Zylstra et al., 2016). As these forests burned regularly (< once every 10 years) prior to European invasion (von Platen et al., 2011), they are highly resilient to repeated fires (Collins, 2020; Prior et al., 2016). In the absence of fire, forest succession can lead to a dense understorey of the cladophyllous tree *Allocasuarina*, or the coniferous tree *Callitris* (Lunt, 1999; Prober et al., 2023, In Press), communities where deep litter mats form that are resistant to fire under moderate conditions but burn intensely under extreme conditions (Fensham, 1992; Gormley et al., 2020; Nicholson et al., 2017). Wet sclerophyll forests, by contrast, naturally experienced much less frequent fire than dry sclerophyll forests. Inter-fire intervals were on average, 37–75 years (McCarthy et al., 1999), but up to 100–300 years (Murphy et al., 2013; Pyrke and Marsden-Smedley, 2005). Wet forest understoreys are dominated by broadleaf mesic trees, that are taller and less flammable than dry forest understorey species (Supplementary Materials Fig. S2, Table 1; Dickinson and Kirkpatrick, 1985). These are killed, without igniting, by low-severity fires, but can act as 'ladder' fuels under dangerous fire weather, carrying flames from the surface to the canopy and causing intense canopy consuming fires (Prior et al., 2022; Sullivan et al., 2012). Many of these understorey species are non-resprouters (Clarke et al., 2015; Cunningham and Cremer, 1965; Prior et al., 2022) that can germinate prolifically only after a low-severity fire under an undamaged canopy where there is inadequate light for *Eucalyptus* regeneration (Cunningham and Cremer, 1965; Prior et al., 2022). As a result, infrequent mixed-severity fires (sometimes only killing the understorey, sometimes causing crown fires; Furlaud, Prior, et al., 2021a; Prior et al., 2022) result in landscape mosaics of multi-aged forests (Turner et al., 2009). A megafire in 1967 caused stand replacement throughout large portions of southeast Tasmania (Solomon and Dell, 1967), rendering large tracts of wet forests relatively young and even-aged, which hence have an increased fire risk (Furlaud, Prior, Williamson and Bowman, 2021b).

In summary, disruptions of Indigenous fire regimes in North America and Australia, and of traditional silvo-pastoral management in Europe, has caused an increase in fuel loads and/or flammability in a spectrum of forest types. This has increased the risk of high-intensity fire in the summer months and made the application of low-intensity fire very difficult (Agee and Skinner, 2005; Covington and Moore, 1994; Veblen et al., 2000). An increasingly common response to this problem in northern hemisphere conifer forests is to mechanically remove ladder fuels and then to intentionally burn the understorey to restore low-intensity fire, and hence the historical fire regime, in such forests (Fulé et al., 2012; Stephens et al., 2012). In contrast, the primary management intervention for Australian forests has historically been the intentional burning of fuels in the forest understorey, without any mechanical treatment (Altangerel and Kull, 2013; Penman et al., 2011), an approach that is known globally as prescribed burning (Fernandes and Botelho, 2003). While both approaches reduce fuel loads, they have strongly contrasting ecological effects and management constraints.

Australian vegetation is generally categorised into different fuel layers (usually some variation of surface, near-surface, elevated, midstorey, and canopy layers) for the study of fire behaviour (Supplementary Materials Table S1; Gould et al., 2008; Hines et al., 2010).

Fig. 1. Diagram of fuel treatments in (a) dry sclerophyll forests and (b) wet sclerophyll forests. Treatments in (a) are, from left to right, mechanical removal of elevated and near-surface fuels (shaded fuel breaks), mechanical removal of elevated fuels only (mechanical thinning), prescribed burning, and untreated forests. Treatments in (b) are, from left to right, shaded fuel breaks, prescribed burning, and untreated forests. Illustration credit Tiana Pirtle. Photo credit John Fisher (left), James Furlaud (right two).

Prescribed burning involves the use of low-intensity fire in moderate weather conditions to consume surface and near-surface fuels, and to reduce ladder fuels through killing, not consuming, plants in the elevated layer (McCaw, 2013; Penman et al., 2011). This generally results in reduced surface fuels and incomplete removal of ladder fuels (Jenkins et al., 2016; McCaw, 2013; Price et al., 2022; Volkova et al., 2014). Prescribed burning is widely used across Australian dry sclerophyll forests, and though it attempts to replicate Aboriginal fire management, modern practices often lack the nuance of traditional practices, and as such they can be quite controversial (Altangerel and Kull, 2013; Bowman, 1998). Prescribed burning cannot be practically applied in many wet sclerophyll forests because of the dense fuels that only dry out under drought conditions (Cawson et al., 2020), and is futile in long unburnt dry sclerophyll forests dominated by cladophyllous understoreys, given the difficulties in burning the dense litter mat under safe fire weather conditions (Fensham, 1992). Additionally, there are risks associated with the need for very specific weather conditions for prescribed burning under a changing climate (Di Virgilio et al., 2020; Kupfer et al., 2020), and the costs to human health of polluting urban airsheds with smoke may outweigh any benefits of fuel reduction achieved through prescribed burning (Borchers-Arriagada et al., 2021).

Mechanical fuel removal, on the other hand, tends to focus only on standing vegetation (Proctor and McCarthy, 2015), and by design removes 'ladder fuels' (the elevated fuels and the mid-storey; Schwilk et al., 2009; Volkova and Weston, 2019). Numerous different fuel reduction treatments have been designed using mechanical techniques, including non-commercial mechanical thinning and removal of small trees and shrubs in the elevated layer, commercial thinning of large understorey trees, and creation of shaded or open fuel breaks, among others (See Supplementary materials Table S1; Agee et al., 2000; Agee and Skinner, 2005; Ximenes et al., 2017). Such treatments have been widely implemented in Europe and North America and can be very effective in moderating extreme fire behaviour (Banerjee et al., 2020; Beverly et al., 2020; Johnston et al., 2021; Parsons et al., 2018), especially when combined with subsequent low-intensity fire (Cansler et al., 2022; Schwilk et al., 2009). As such, mechanical treatments have enabled successful reintroduction of low-severity fire into forests with disrupted fire regimes (Fulé et al., 2012; Roccaforte et al., 2008), while minimising adverse ecological effects (McIver et al., 2013). Mechanical treatments are still in their infancy in Australian sclerophyll forests (Keenan et al., 2021), however, and their effects in the context of *Eucalyptus* forests are poorly understood. Several studies have focused on mid-storey removal (Taylor, Blanchard and Lindenmayer, 2021a; Volkova et al., 2017; Volkova et al., 2014; Volkova and Weston, 2019), or mastication of shrubs encroaching into *Eucalyptus* woodland (Grant and Wouters, 1993; Pickering et al., 2022). No Australian study, however, has focused on the mechanical removal of only the elevated or near-surface fuels, despite the primacy of these fuels in driving fire behaviour (Hines et al., 2010; Zylstra et al., 2016). In contrast to prescribed burning, mechanical treatments are not constrained by fire weather or concerns around smoke pollution (Borchers-Arriagada et al., 2021). Given the potential advantages of mechanical treatments, and given their current lack of implementation in Australia, a comparison of prescribed burning and mechanical removal of near-surface and elevated fuels is required.

Both mechanical treatments and prescribed burning will likely aridify forest microclimate by reducing the understorey cover that maintains cool, moist conditions (Kovács et al., 2017; Norris et al., 2012). This will, in turn, increase the availability of surface fuels to burn, a key switch for the occurrence of wildfires (Bradstock, 2010; Cawson et al., 2017). Further, fuel moisture is an important determinant of fire behaviour once a fire has been ignited, reducing rate of spread and flame height (Cruz et al., 2022). Hence, there is a fundamental trade-off between the reduced fire hazard through fuel reduction and the increased fire hazard through aridification of the microclimate following removal of the understorey. Understanding the net effect of these two contradicting influences is essential to evaluate the effectiveness of these treatments in altering fire behaviour.

Accordingly, in this paper we attempt to quantify the fuel reduction

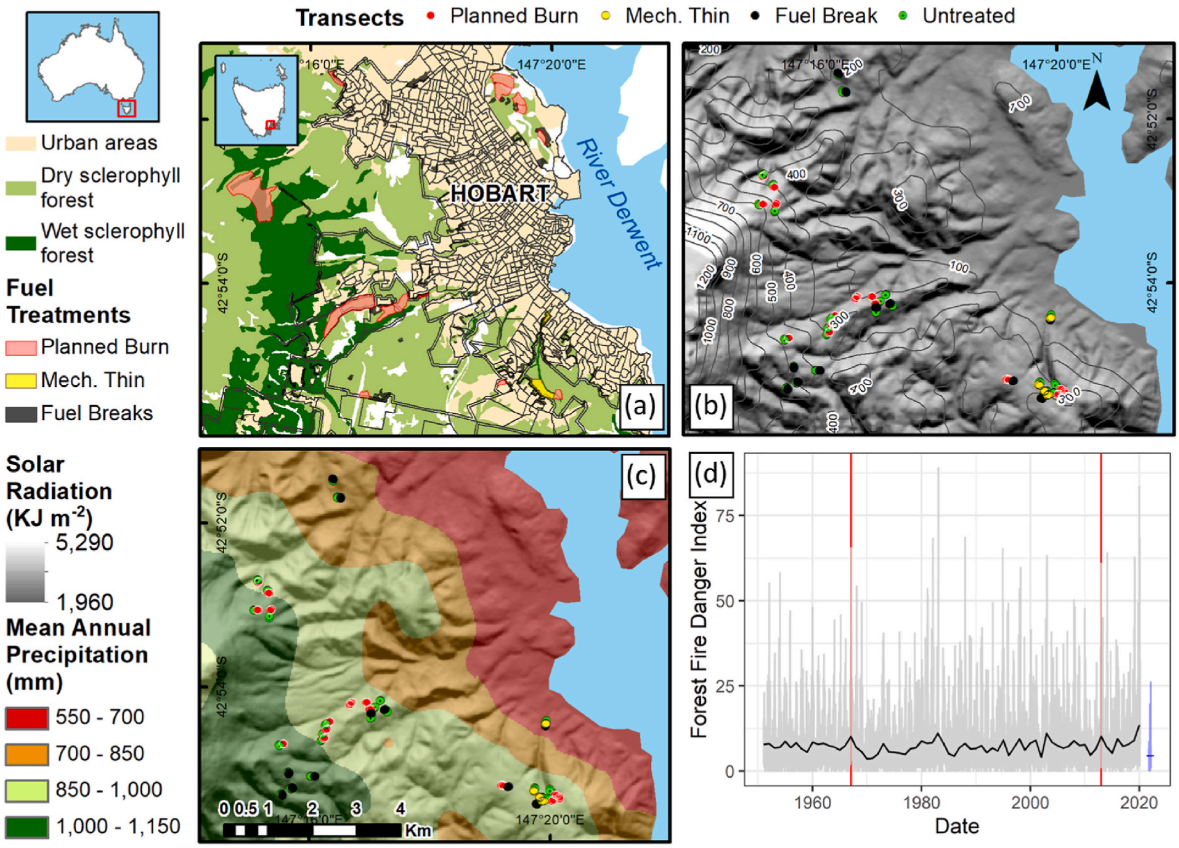

Fig. 2. Maps of the (a) vegetation and urban areas, (b) topography, (c) macro- and micro-climate in the study area, along with (d) a graph describing the climate history. (a) Urban layout of Hobart with the extent of wet and dry sclerophyll forests shaded as indicated and with the extent of the 2020/21 City of Hobart fuel treatment plan represented by coloured polygons as indicated. (b) Elevation (contours in metres) and grey-scale shading showing annual solar radiation with coloured coded points indicating the location of transects. (c) Colour coded mean annual precipitation gradient, and integrated solar radiation shaded to indicate microclimate differences. Maps use the projected coordinate system Geocentric Datum of Australia (2020), MGA Zone 55. (d) Shows modelled regional climate data between 1950 and 2020 [from Dowdy (2020); See Supplementary methods]. Grey tracing indicates daily maximum modelled Forest Fire Danger Index (FFDI), and black tracing indicates the annual mean from summer months (November–February; same as study period). Blue tracing indicates observed daily maximum FFDI values recorded at the local meteorological station during our study period, with the dark line indicating the summer mean. Red bars indicate the days of southern Tasmania's two worst fire disasters (February 7, 1967 and 4 January 2013). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

and understorey microclimate effects induced by three different fuel removal techniques (shaded fuel breaks, mechanical thinning, and prescribed burning) and understand how this affects potential fire severity. We consider forests on kunanyi/Mt. Wellington in the WUI of Hobart, the capital city of Tasmania. Hobart is a particularly fire-prone city, with numerous WUI suburbs in close proximity to wet and dry sclerophyll forests, in a region where WUI fuels treatment is of particular importance (Penman et al., 2020). Forests on the slopes of kunanyi are an ideal test case: due to their mid-latitude location (43°S), there are substantial differences in solar radiation between polar (south) and equatorial (north) facing slopes (Holland and Steyn, 1975). This leads to different microclimates and hence a diverse mosaic of wet and dry sclerophyll forests in a similar environment (Kirkpatrick and Nunez, 1980). In particular, we focus on dry forests that are long unburnt, and wet forests that are even-aged, many of which were last burned in the 1967 Black Tuesday fire (Table 1). These forests present significant challenges for contemporary fire management approaches based around prescribed burning.

In this paper we make snapshot estimates of changes in fuel load, microclimate, and resultant likelihood of high-severity fire, following the recent (less than one year) implementation of mechanical fuel treatments and prescribed burning. We ask three questions: (i) Do these treatments effectively reduce fuel load? (ii) What are the differences in understorey microclimate in each of these treatments as compared to untreated forests? And (iii) How do these differences in fuel load and microclimate translate to differences in the potential for canopy damaging fires? To answer these questions, we measured fuel load in the surface, near-surface, and elevated layers across 61 transects in suburbs in the WUI around Hobart. We then placed dataloggers in the litterpack to measure temperature and humidity for an entire fire season. We used fire behaviour equations specific to sclerophyll forests and observed weather data to calculate expected flame height and the resultant likelihood of crown fire and canopy scorch. We used this data to assess the ability of these treatments to restore low-intensity fire to the ecosystem. This exercise allows us to provide management recommendations to forest managers so that they can make informed decisions about restoring ecosystem function and protecting communities on the WUI, especially in Southern Australia.

2. Methods

2.1. Study sites

Our study area is located in dry and wet sclerophyll forests on the outskirts of Hobart. The area has a mean annual temperature of 11 °C and a mean annual precipitation of 670 mm. Dry sclerophyll forests occupy rocky soils on ridgelines and north-facing slopes, and wet sclerophyll forests occupy deeper organic soils in gullies and on south facing

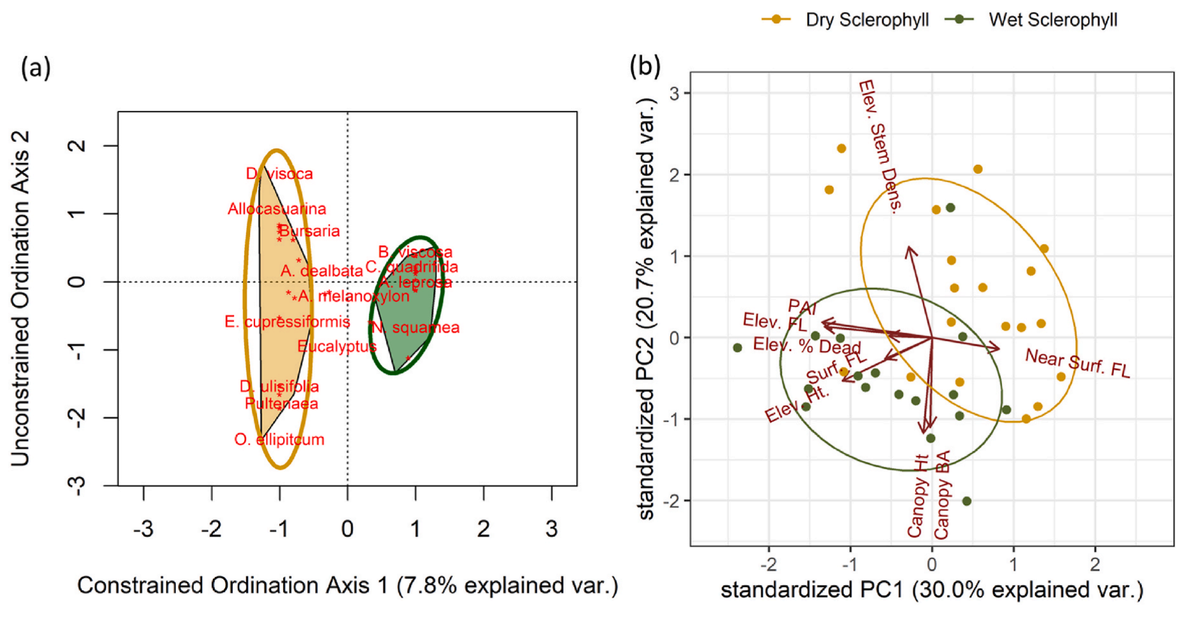

Fig. 3. Differences between forest types. Ordination biplots representing (a) the first constrained axis and the second unconstrained axis from a constrained correspondence analysis (CCA) to test for differences in floristics, and (b) the first two standardised principal components of a principal components analysis (PCA) to investigate structural differences. In the CCA plot the most abundant species/genera are listed, less abundant species are represented by *. In the PCA plot the arrows represent loadings for the different structural variables. Coloured hulls and ellipses represent associations with a specific forest type. Variable abbreviations are explained in Supplementary materials Table S8.

slopes (Fig. 1; Kirkpatrick and Nunez, 1980). There is a mix of igneous and sedimentary rock types which also influence vegetation productivity, particularly in dry forests (Fensham, 1992).

We selected 8 areas with similar floristics to measure vegetation (hereafter 'study sites'). Our study sites were located in areas ranging in elevation from 20 m to 620 m and were mostly on dolerite regolith. Four sites were located in dry sclerophyll forests (*Eucalyptus pulchella* and *Eucalyptus globulus* canopy with a shrubby understorey, including *Pultenaea juniperina*, *Dodonaea viscosa*, *Bedfordia salicina*, and *Allocasuarina verticillata*). Fuels are frequently dry enough to burn in these dry forests (roughly 80–90% of the summer; Slijepcevic et al., 2018), as a result of the high incident solar radiation on north-facing slopes (Nyman et al., 2015), and a sparse understorey (PAI, see Supplementary materials Table S2; Pickering et al., 2021), which reduces the thermodynamic efficiency of the microclimate (Norris et al., 2012). Four sites were located in wet sclerophyll forests (*Eucalyptus obliqua* canopy with a broadleaf understorey – including *Acacia melanoxolon*, *Nematolepis squameum*, and *Comprosma quadrifida*). Fuels in these wet forests are dry enough to burn up to 4 times less frequently than in dry forests (Slijepcevic et al., 2018), due to reduced solar radiation on south facing slopes (Nyman et al., 2015), and a denser understorey that more effectively retains moisture (PAI; see Supplementary materials Table S2; Cawson et al., 2017; Kovács et al., 2017; Pickering et al., 2021).

Sites were selected using planned fuel treatment maps provided by the City of Hobart (CoH) and set up in April 2021 (Fig. 2). CoH is implementing different fuel reduction treatments around Hobart suburbs: BAL-29 shaded fuel breaks (Agee et al., 2000; Standards Australia, 2009), which mechanically remove near-surface and elevated fuels, mechanical thinning of elevated fuels only (Ximenes et al., 2017), and low-intensity prescribed burning, which targets the surface and near-surface layers (Fig. 1; Fernandes and Botelho, 2003). These treatments, especially the mechanical treatments, generally focused on forests that managers normally do not target for prescribed burning due to large surface fuel loads and dense understoreys resulting from fire exclusion for up to 50 years. Indeed, many were last burned during the 1967 'Black Tuesday' fires. In the case of dry forests, target stands had developed dense *Allocasuarina*-dominated understories, and in the case of wet forests, target stands were even-aged 1967 regeneration (Table 1; pers. comm. E. Jeffrey March 2021). All three treatments were implemented in dry forests, while only shaded fuel breaks and prescribed burning were implemented in wet forests, as there are few functional differences between fuel breaks and mechanical thinning in wet forests due to a lack of near-surface fuels. We used a modified paired treatment-control design, based on availability of treated and untreated areas at a given site. For more details on study design and transect placement see Supplementary Materials Section S.1a.

2.2. Field methods

2.2.1. Fuel transects

Between April and November 2021, we measured 61 transects around Hobart. At each transect we measured fine fuel load and vegetation structure. We sampled three fuel layers typical in most sclerophyll forests (supplementary materials Table S1; Gould et al., 2007; Hines et al., 2010): (i) surface fuels, the leaf and twig litter on the ground; (ii) near-surface fuels, live and dead fuel touching the surface but not lying on it; and (iii) elevated fuels, the live shrubs and small trees in the understorey.

2.2.1.1. Surface and near-surface fuels. To measure surface and near-surface fine fuel loads, we set up 1 × 1 m quadrats in two regularly-spaced locations along the transect tape. Within each quadrat, we collected all the attached, live herbaceous fuels (defined as all vascular plants <0.5 m in height and all ground ferns), live grasses, and dead fine fuels (defined as all detached dead material, including twigs <0.6 cm in diameter). This last category constituted the surface layer, and everything else constituted the near-surface layer. We removed all collected samples and dried them in an oven at 80 °C to a constant weight. In transects with no elevated fuel layer, we set up two extra quadrats for the surface and near-surface fuels.

2.2.1.1. Elevated fuels. To measure fuel load and physiognomy in the elevated layer, we sampled rectangular subplots along the transect,

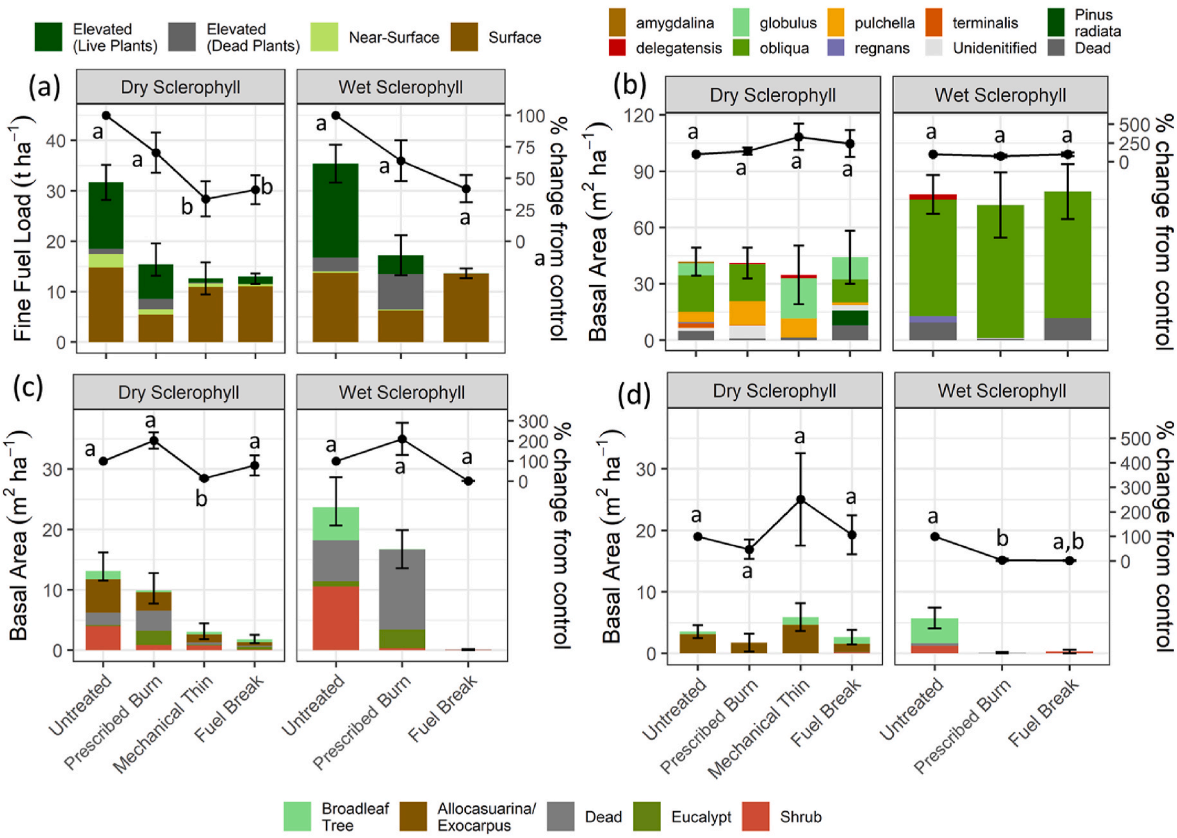

Fig. 4. Stacked bar charts illustrating the effect of treatments on (a) mean fine fuel load in the different fuel layers, basal area of (b) elevated and (c) mid-storey trees and shrubs for each functional type, and (d) basal area of canopy trees for each species of *Eucalyptus* and the introduced *Pinus radiata*. Bars are shaded as indicated to represent proportions in each category. Point and line plot above the bars indicates the pairwise percent change in the indicated variable (axis on right side) associated with each treatment, with alphabetical annotation indicating statistical significance according to a paired *t*-test based on fuel load/basal area.

adjusting the area of each subplot to capture five plants. We considered any woody plant that was >0.5 m tall, and <10 cm in diameter at a breast height of 1.3 m (d_{bh}) to be in the elevated layer. To measure plants in this layer, we split the transect into four 7 m long segments. In each of these 7 m segments we measured the five live individuals that were closest to the transect (up to a maximum distance of 7 m from the transect tape) to create a variable area rectangular subplot. We recorded the species of each individual plant and measured the basal diameter at 10 cm above ground (d_{10}), top height (*Ht*), height to base of live crown (*HCB*), and d_{bh} of each plant >0.5 m in height.

We also visually estimated canopy area, using canopy width estimates along two perpendicular lines (Similar to Fig. 3 in McColl-Gausden and Penman, 2019) to calculate the area of an oval surrounding the canopy. In transects subject to prescribed burning we also assessed the intensity of the prescribed burn using two fire intensity correlates: we measured the average diameter of all burnt branch tips between 1.1 and 1.5 m aboveground, and the height of charring on the stem for each plant.

We also recorded the location of each plant using *x* and *y* coordinates, with the *x* coordinate represented by the distance along the transect and the *y* coordinate represented by the distance from the transect. In uniformly dense understoreys, we measured the five individuals closest to the tape in a 1 or 2 m subsection at the centre each of the 7 m segments. We then calculated the area of the subplot by measuring the perpendicular distance from the transect of the farthest plant on each side and multiplying this by the segment length (7 m) or the subsection length (1 or 2 m). We repeated these methods for the five closest dead elevated stems to the transect, but measuring only d_{10} or d_{bh} and *Ht*.

2.2.1.3. Mid-storey and canopy fuels. To measure fuel load and forest structure in the mid-storey and canopy layers, we used circular plots. We adjusted the radius of each plot to capture roughly five live trees >10 cm d_{bh}. If the plot only captured trees in the mid-storey, we added a second subplot to capture at least two live trees in the emergent canopy layer. For each tree we measured the d_{bh}, *Ht*, and *HCB*. Heights were measured using a Vertex Hypsometer (Haglöf Sweden AB; https://haglofsweden.com/). We also measured the d_{bh} and *Ht* of all dead trees within each plot.

2.2.2. Understorey microclimate measurements

To measure understorey microclimate, we placed one Hygrochron iButton® (Maxim/Dallas Semiconductor Corp. Sunnyvale, CA, USA) in the litterpack 10 m from the start of each transect, except for the seven transects in forests for which treatments had not yet been implemented, and the four transects at northernmost site (Fig. 1d), due to operational constraints. This resulted in iButtons being placed in 54 transects. The iButtons were housed in white 3D-printed casings following the methods of Nyman et al. (2015). We programmed them to take hourly measurements of temperature and relative humidity between the dates of 5 October 2021 and 10 March 2022. Due to equipment failure or loss, we were able to recover data from only 44 of the 54 ibuttons deployed.

2.3. Data analysis

2.3.1. Fuel load and physiognomy

2.3.1.1. Surface and near-surface fuels. To profile fuel load and structure in different forests, we estimated the mass (t ha^{-1}) of dead fine fuels (leaves, branches, and stems <0.6 cm in diameter), and coarse fuels

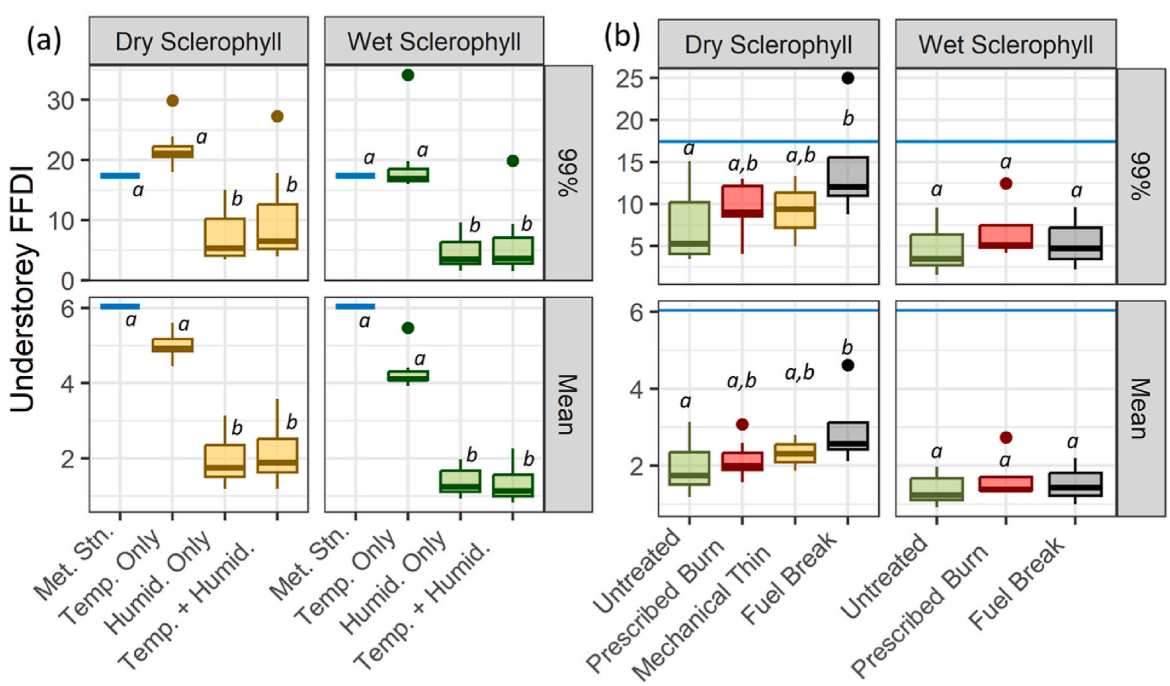

Fig. 5. The effect of microclimate on fire danger. (a) Displays FFDI estimates, calculated using temperature and humidity measurements from a meteorological station (left), using temperature from the litterpack and humidity from the meteorological stations (left centre), using humidity from the litterpack and temperature from the meteorological station (right centre), and using temperature and humidity from the litterpack (right). (b) Displays the difference in understorey FFDI between treatments, with understorey FFDI calculated using humidity from the litterpack and temperature from the meteorological station. Values are presented from all days (bottom) and only 99th percentile and above days (top).

(twigs ≥0.6 cm but <1.5 cm diameter) in the surface layer, and of living fuels in the near-surface layer (living plants <0.5 m in height), by scaling up corresponding masses in the quadrats.

2.3.1.2. Elevated fuels, mid-storey, and canopy. We then estimated the biomass in the elevated layer of fine fuels in live plants (foliage and twigs <0.6 cm diameter), and in dead plants (twigs only, as leaves had generally fallen to the ground) using allometric equations. Where possible, we used already published equations, otherwise we used published data to develop our own equations for non-eucalypt trees (Kieth et al., 2000; Paul and Roxburgh, 2017; Paul et al., 2016). In total, seven equations were used to predict an individual's biomass from its d_{bh} or d_{10}, one for each of the four growth form classes recorded in the plots (see Supplementary materials Table S8). For further analyses of fuels, we split each transect into two sub-transects, pairing elevated fuel load estimates from two adjacent subsections with surface and near-surface estimates from a single quadrat.

2.3.1.3. Comparison of fuel load, stand structure, floristics, and physiognomy. We compared the physiognomy and floristics of wet and dry forests to determine how they differed, an important consideration given they occur along moisture gradients and can intergrade, particularly when they are long unburned. To test that the two forest types are distinct ecological systems, we used a constrained correspondence analysis (CCA) to test for differences in species composition. We used CCA because our floristics dataset was sufficiently heterogeneous to require a unimodal ordination method: detrended correspondence analysis indicated gradient lengths were greater than 4 standard deviations (8.3 SD). We used a species abundance matrix from the elevated fuel layer to perform the CCA, and the only environmental factor included in the environmental matrix was forest type. In the cases of particularly diverse genera that occurred exclusively in one forest type, we grouped all species into one genus for the analysis. We then used a permutation test (with 999 permutations) to determine if the floristics were significantly different between forest types. We used principal components analysis (PCA) to investigate how structural variation differed between forest types. Full names of variables included in the analysis are listed in Supplementary materials Table S2. Lastly, we compared the relative effectiveness of each of the three treatments in reducing fuel load and basal area, and in altering understorey floristics. To do this we used paired t-tests to see if there was a significant change in the variable affected, using paired treatment and control transects from the same study site as sampling units. In the case of variables describing the surface, near-surface, and elevated layer, where we had two subsamples per transect, we use a nested random effect with sub-transects as sampling units. The variables we tested are listed in Table S2.

2.3.2. Characterisation of understorey microclimate

2.3.2.1. Comparison of microclimate effects. To understand the effectiveness of the understorey microclimate at buffering temperature and humidity, we compared our hourly measurements with hourly data from the closest local meteorological station that had hourly measurements (EPA Tasmania, New Town; https://epa.tas.gov.au/environment/air/monitoring-air-pollution/monitoring-data/real-time-air-quality-data-for-tasmania/hobart-(new-town)). We compared understorey microclimate effects on temperature and humidity in the litterpack, testing whether litterpack measurements differed significantly from the weather station observations and between forest types and treatment types. For this we used repeated-measures gamma generalised linear mixed effects models (GLMMs). For more details see Supplementary Materials S.1.2.1.

2.3.2.2. Effect of microclimate on fire behaviour. To determine whether treatments changed understorey microclimates enough to affect fire behaviour, we calculated McArthur's Forest Fire Danger Index (FFDI; Noble et al., 1980) at 15:00 h from the nearest weather station (Bureau

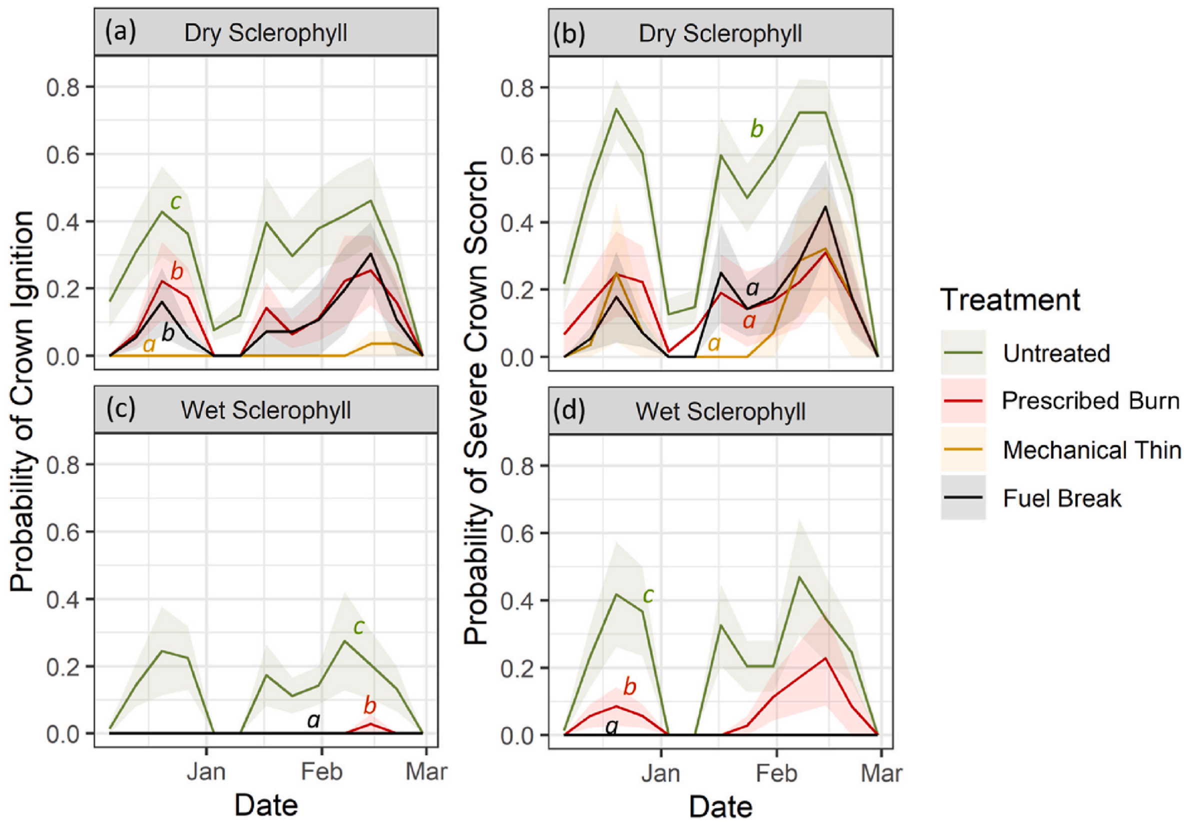

Fig. 6. The effect of treatments on potential summer fire severity across multiple sites in wet and dry sclerophyll forests. Plots show weekly average fire severity metrics plotted by date: in (a,c) the probability of crown ignition, and (b,d) the probability of severe crown scorch. Coloured lines represent treatment-level means, with ribbons representing one standard error, as indicated. Alphabetic annotation indicates statistical significance according to generalised linear mixed effects models.

of Meteorology, Hobart; http://www.bom.gov.au/climate/dwo/IDCJDW7021.latest.shtml) for every day during the study period. We (a) investigated whether differences in litterpack temperature and humidity (compared to the weather station) were substantial enough to significantly reduce FFDI, and (b) if the resulting understorey FFDI calculation differed significantly between treatments. We did this using repeated-measures gamma GLMMs. For more details see Supplementary Materials S.1.2.2.

2.3.3. *The trade-off between fuel load and microclimate*

To assess the trade-off between reduced fuel loads and drier microclimates, we estimated potential fire behaviour variables.

2.3.3.1. Availability to burn. We started by estimating availability to burn of surface litter. We used FMI to estimate the fine fuel moisture content by weight (FFMC; %) of the surface fuels using published equations from Nyman et al. (2015). We used this estimate to identify days during the study period in which FFMC <17%, the moisture content at which *Eucalyptus* litter can sustain a fire, as days in which the forests could burn.

2.3.3.2. Estimating potential fire severity. We then estimated rate of spread (ROS), potential flame heights (f_{ht}) and scorch height (S_{ht}) for each day in which fuels were dry enough to burn. We used the empirically-derived McArthur's Mk5 fire behaviour equations (Noble et al., 1980), which predict rate of spread (km hr^{-1}) and flame height (not length; m) of fire as a function of fuel load, fire weather, and slope. They underpin Phoenix Rapidfire, the standard operational fire behaviour model for southeast Australian fire agencies (Neale & May 2018; Tolhurst et al., 2008). We then used an equation from Gould (1994) to predict scorch height (m). The equations are as follows:

$$ROS = 0.0012\ FFDI \times FL \times e^{0.069 slp} \quad (1)$$

$$f_{ht} = 13\ ROS + 0.24\ FL - 2 \quad (2)$$

$$S_{ht} = 5.232\, f_{ht}^{\ 0.756} \quad (3)$$

where.

FFDI is McArthur's Forest Fire Danger Index,

FL is fuel load (t ha^{-1}),

and

Slp is the topographic slope of the site (degrees).

We estimated rate of spread, flame height, and scorch height of potential fires on every day during our study period in which surface fuels were dry enough to burn. To do this we performed a simple mechanistic implementation of the McArthur model to incorporate the effects of fuel moisture and vertical arrangement (details of this process are provided in the Supplementary Materials, section S.1). If our predicted f_{ht} exceeded the average height to crown base (*HCB*) of the *Eucalyptus* canopy, we considered this a day in which crown ignition was possible. If our predicted S_{ht} exceeded the mean canopy top height, we considered this a day in which severe crown scorch was possible. We then used repeated-measure binomial GLMMs (with χ^2 tests in an identical manner to 2.3.2.1) to test if the likelihood of crown ignition and the likelihood of severe crown scorch were significantly different between treatments.

All statistical and graphical analyses were performed in R (R Core Team, R Foundation for Statistical Computing, Vienna, Austria; http://www.R-project.org/) using the packages 'ecbtools' (Grant Williamson, University of Tasmania https://rdrr.io/github/ozjimbob/ecbtools/), 'lme4' (Bates et al., 2015), and 'vegan' (Oksanen et al., 2022). All geographical analyses were performed in ArcGIS geospatial software (ESRI Inc., Redlands, CA, USA, www.esri.com).

3. Results

3.2. Fuel loads, physiognomy, and floristics

3.1.1. Untreated forests

Wet and dry forests had substantial floristic and physiognomic differences between them. Dry forest understoreys tended to be dominated by the cladophyllous *Allocasuarina* spp. and *Exocarpus cupressiformis*, and needle-leaved shrubs such as *Bursaria* spp., *Pultanea* spp., and *Dodonea viscosa*. Wet forest understoreys, meanwhile, were dominated by broadleaf trees and shrubs such as *Beyeria viscosa*, *Acacia leprosa*, and *Nematolepis squamea* (Fig. 3a). CCA analysis revealed these floristic differences resulted in statistically distinct understorey assemblages ($P = 0.01$), with the first and only constrained ordination axis explaining 7.8% of the variation (Fig. 3a). Note that in Fig. 3a the y-axis is an unconstrained ordination axis and hence is not included in the statistical analysis, it is only included for visualization purposes. While both forests were dominated primarily by the resprouter *Eucalyptus obliqua*, dry forests had a much more diverse assemblage of *Eucalyptus* species in the canopy than did wet forests (Supplementary Materials S1c). The two forests types were not as distinct structurally as they were floristically, but there were still substantial differences (Fig. 3b): wet forests had taller, more well stocked canopy, a taller elevated layer, denser foliar cover in the understorey, and more dead stems. Dry forests had more near-surface fuels (namely bracken and grasses), and a higher stem density in the elevated layer (despite a lower foliar cover, likely due to the elevated plants' slender leaves). The strongest loadings on the first principal component (which explained 30% of the variation) were for variables in the elevated and near-surface layers, whereas the largest loadings on the second principal component (explaining 20.7% variation) were for elevated stem density, and canopy height and basal area (Fig. 3b, Supplementary Materials Table S3).

3.1.2. Effect of fuel treatments

3.1.2.1. Dry sclerophyll forests. In dry forests, we found mechanical thinning and shaded fuel breaks to be more effective at reducing total understorey fine fuel load (inclusive of all layers) than prescribed burning (Fig. 4a; Supplementary Materials Table S3). Model results indicated that, on average, fuel breaks reduced fine fuel load by 23.9 t ha^{-1} and mechanical thinning reduced it by 37 t ha^{-1}, both statistically significant reductions ($P = 0.04$; Supplementary Materials Table S3). Meanwhile, prescribed burning reduced total fuel load by 9.4 t ha^{-1}, however this was not a statistically significant reduction, due to high variability in the untreated forests ($P = 0.058$; Supplementary Materials Table S3). Fuel-reduction effects were restricted to specific fuel layers for different treatments: mechanical thinning significantly reduced fine fuel load in live elevated fuels ($P = 0.008$), and planned burning significantly reduced surface fuels by 7.1 t ha^{-1} ($P = 0.003$) and near-surface fuels by 3 t ha^{-1} and $P = 0.04$ (Table S3). No other layer exhibited a significant reduction in fuel load. However, mechanical thinning also made substantial changes to the structure of the forests, significantly reducing overall elevated basal area (by 23.4 m^2 ha^{-1}; $P = 0.01$), basal area in shrubs (by 6.1 m^2 ha^{-1}; $P = 0.04$), and plant area index (PAI; by 2; $P = 0.01$). The other treatments did not make significant structural changes. There was no relationship between the severity of the prescribed burn at each site and the effects of the treatment, despite substantial variation in the severity of prescribed burns in our study area (Supplementary Materials Fig. S3).

3.1.2.1. Wet sclerophyll forests. In wet forests fuel breaks and prescribed burning reduced overall fuel load, on average, by a similar magnitude as in dry forests, however due to the small sample size, these differences were mostly not statistically significant (Fig. 4a). Both treatments essentially eliminated the elevated layer providing the understorey microclimate, significantly reducing PAI (by 1.4; $P = 0.007$). Prescribed burning had the added effect of killing most non-*Eucalyptus* trees in all layers, hence significantly increasing the fuel load and basal area of dead plants in both the elevated (by 3.4 t ha^{-1} and 5.3 m^2 ha^{-1}; $P = 0.028$ & 0.048) and mid-storey (by 0.9 m^2 ha^{-1}; $P = 0.022$) layers, and reducing the basal area in broadleaf trees in the elevated layer (by 1.8 m^2 ha^{-1}; $P = 0.028$). Prescribed burning also significantly reduced fuel load in surface fuels (by 10.6 t ha^{-1}; $P = 0.002$). By design, no treatment had any substantial effect on the canopy (Fig. 4c). The severity of the prescribed burns had a similarly negligible effect as in dry forests.

3.3. Microclimate

3.2.1. Understorey microclimate in untreated forest

We found that both wet and dry forest understoreys had a consistent and significant effect of creating a moist microclimate in untreated

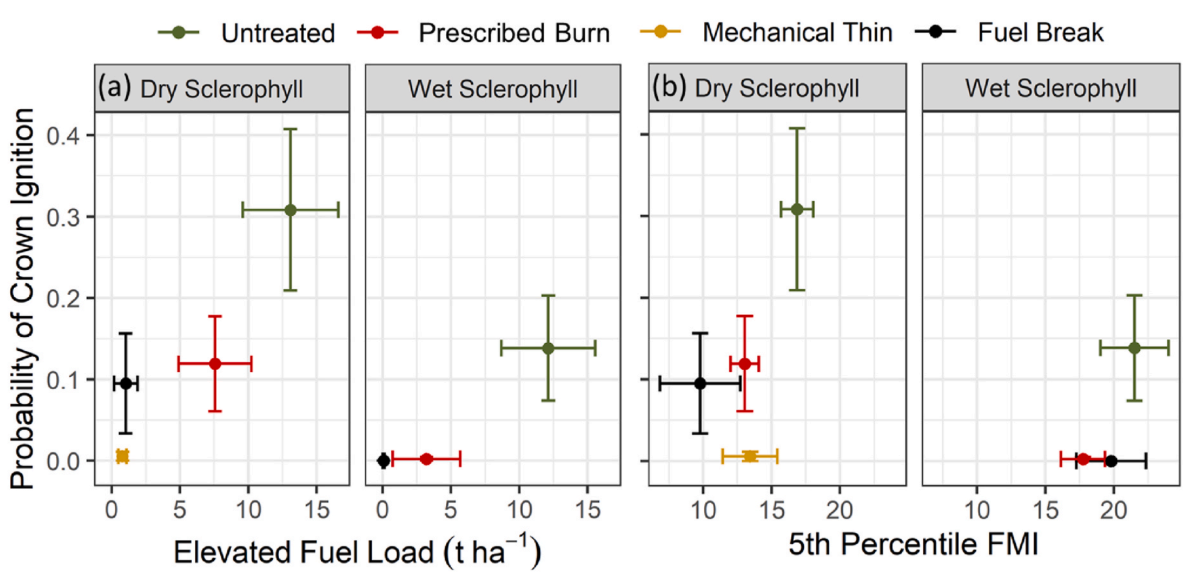

Fig. 7. Ordination of summer average probability of crown ignition vs. (a) fuel load, and (b) 5th percentile Fuel Moisture Index (FMI) across the transects for each treatment and forest type. Error bars represent one standard error reflecting variation between the transects. Points and lines are coloured as indicated.

forests. Wet forests had a substantially cooler, moister understorey microclimate than dry forests, with an expected summer 3pm temperature 2.8°C lower than the meteorological station, a relative humidity 47% higher, and a FMI 11 higher (Supplementary Materials Fig. S4). Meanwhile, dry forest microclimate was moister but warmer than the meteorological station, with expected summer 3pm temperature 1.3° warmer than the meteorological station, and relative humidity and FMI 44.3% and 7.7 higher than the meteorological station respectively. All of these differences were significant ($P < 0.001$; Supplementary Materials Fig. S4).

3.2.2. Effect of fuel treatment on understorey microclimate

3.2.2.1. Dry sclerophyll forests. In dry forests, the two mechanical removal techniques substantially altered understorey microclimate, whereas prescribed burning did not (Supplementary Materials Fig. S5). Mechanical thinning and fuel breaks significantly increased expected summer 3pm understorey temperature by 3.3 and 2.9°C, respectively, and significantly decreased expected summer 3pm relative humidity by 8.1% and 9.6%. This resulted in reductions in FMI of 2.4 and 4.2 for the two treatments, respectively (Supplementary Materials Fig. S5). Meanwhile the only significant microclimate change from prescribed burning was an increase in temperature of 2.6°.

3.2.2.1. Wet sclerophyll forests. In wet forests, the effects of prescribed burning on understorey microclimate were statistically significant but the effect size was minor (Supplementary Materials Fig. S6). Prescribed burning significantly increased expected summer 3pm understorey temperature by 2.1° and decreased expected summer 3pm relative humidity by 0.7% and FMI by 0.4. Fuel breaks significantly reduced average temperature, but had no other significant effect on understorey microclimate.

3.2.3. Effect of understorey microclimate on fire danger

We used empirical measurements of understorey temperature and humidity to investigate how these components of understorey microclimate can affect fire danger. We found the incorporation of understorey relative humidity measurements into FFDI calculations significantly reduced FFDI when compared to the meteorological station, both when using all observations and observations on 99th and above percentile days (Fig. 5a). On average, FFDI decreased from 19 to 8 in dry forests ($P < 0.001$), and 19 to 5 in wet forests ($P < 0.001$; Supplementary Materials Table S4) on 99th percentile FFDI days. The addition of understorey temperature, however, did not significantly change FFDI, regardless of whether or not we included understorey relative humidity in our calculations (Fig. 5a, Supplementary Materials Table S4). As a result, we considered the best performing predictor of understorey FFDI to be the calculation that included understorey relative humidity but not temperature in calculating FFDI.

Using this calculation of understorey FFDI we compared differences in understorey FFDI between treatments. We found that, though changes in understorey humidity can influence FFDI, and though there were differences in understorey microclimate between treatments, especially in dry forests, these differences did not result in significantly different understorey FFDI estimations between the different treatments (Fig. 5b, Supplementary Materials Table S5). The one exception was fuel breaks in dry forests, where the FFDI was, on average, 6 higher in the fuel breaks than in untreated forests.

3.4. Potential fire severity

In assessing the trade-off between reduced fuel and drier understoreys associated with different treatments, we found that, for both forest types, the effect of a reduced fuel load overrode the effect of a drier microclimate, and all treatments reduced predicted fire severity. In particular, mechanical treatments (thinning in dry forests and fuel breaks in wet forests) exhibited the capability of eliminating the possibility of crown ignition, but prescribed burning also resulted in significant reductions in fire severity (Fig. 6; Supplementary Materials Table S6).

3.3.1. Dry sclerophyll forests

In dry forests, we found that all three treatments significantly reduced potential fire severity, and that mechanical thinning was particularly effective at reducing the likelihood of a crown fire. Mechanical thinning almost eliminated the possibility of crown ignition in our study period: the probability of crown ignition was reduced from 0.25 in untreated forests to 0 in mechanical thinned sites, whereas this probability was 0.06 in fuel breaks and 0.05 in prescribed burns ($P < 0.0001$; Supplementary Materials Table S6; Fig. 6a). Meanwhile, all three treatments were similarly effective at reducing the subsequent risk of severe crown scorch. The expected probability was reduced from 0.44 in untreated forests to 0.07 in fuel breaks, 0.06 in prescribed burns, and 0.05 in mechanically thinned forests ($P < 0.0001$; Fig. 6b; Supplementary Materials Table S6).

3.3.2. Wet sclerophyll forests

In wet forests, both treatments also led to significant reductions in fire severity. Fuel breaks, in particular, almost eliminated the potential for crown damage, reducing the probability of crown ignition from 0.11 to 0 and of severe crown scorch from 0.12 to 0 ($P < 0.0001$; Fig. 6c; Supplementary Materials Table S6). Prescribed burns also significantly reduced expected fire severity, but to a lesser degree: the probability of crown ignition and scorch were reduced to <0.02, but not eliminated ($P < 0.0001$; Fig. 6d; Supplementary Materials Table S6).

4. Discussion

In this study, we used empirical measurements of fuels and microclimate to assess the potential for three different fuel treatments to reintroduce low-severity fire into wet and dry *Eucalyptus*-dominated sclerophyll forests with altered fire regimes. The wet and dry sclerophyll forests in our study had markedly different floristics, but the differences between their fuel load and physiognomy were not as pronounced. We found treatments reduced fuel load and understorey cover, and removed the most flammable fuel types. However, treatments also reduced humidity and increased temperature in the forest understorey, though the understorey in treated forests was still substantially moister than outside the forests. We determined that the contrasting influence of reduced fuel load and increased understorey dryness still resulted in significantly reduced subsequent fire severity, indicating that all treatments have the capability to reintroduce low-severity fire into wet and dry sclerophyll forests. Here, we discuss in detail what our results reveal about the effectiveness of these treatments and how the results in our study area compare to similar studies from different regions globally. Lastly, we discuss the limitations of our study and the broader management implications of the results.

4.1. Effects of treatments on fuel load and structure

We found floristics differed significantly between wet and dry sclerophyll forests. Dry forests had a diverse canopy, with six species of *Eucalyptus,* and an understorey dominated by highly combustible cladophyllous trees and needle-leaved shrubs. Meanwhile wet forests had only three species of canopy trees, but were more densely stocked, and were dominated by less-flammable broadleaf mesic trees in the understorey. These structural differences, particularly the dense broadleaf understorey (Supplementary materials Figure S2; Pickering et al., 2021), result in wet forests having cooler, moister understoreys. These are defining differences between wet and dry sclerophyll forests in Tasmania and across Australia, and in our study area are the result of differences in productivity related to differences in microclimate and solar radiation (Fig. 2c; Duncan and Brown, 1985; Kirkpatrick et al., 1988; Little et al., 2012). This is why we treat these forests as separate systems. However, it is important to note that the differences in overall understorey fuel load were not significant (Supplementary materials Table S2). This is likely a function of the interplay of high fuel loads in long unburned dry forests, and of wet forests having lower fuel loads because they are on the drier end of their range and intergrading into dry forests.

4.1.1. Dry sclerophyll forests

Our results indicated that, all treatments reduced overall fuel load, but this difference, relative to control sites, was only significant in mechanical treatments. These treatments, on average, removed substantially more fuel (by 2.4–4 fold) than burning. However, the three treatments had different effects on the structure and distribution of fuel load among layers, as each targeted different layers. For example, prescribed burning significantly reduced surface fuel load but failed to significantly change fuel load in live elevated fuels. Meanwhile, mechanical treatments reduced elevated fuel load and hence foliar cover but had little effect on surface fuels. Previous studies in dry forests have demonstrated a reduction in surface fuel loads associated with prescribed burning (Bennett et al., 2014; Hollis et al., 2011). While the effect of prescribed fire and wildfire on elevated fuel loads is less studied, Volkova et al. (2019) indicated that elevated fuel loads can quickly exceed pre-fire levels in the years directly following a burn. The intensity of a prescribed burn may have important implications for its effects on fuel load and its ecological impacts (Johnson and Miyanishi, 1995). However, despite the relatively high variation in the intensity of the prescribed burns in our study (Supplementary Materials Fig. S3), we found no relationship between the intensity of the prescribed burns and their effects on fuel structure. This may have been due to our small sample size, however, and needs further investigation. It is important to note that many of these prescribed burns would have been extremely low-severity, low enough that they would likely be undetectable with satellite-derived metrics such as difference normalised burn ratio (dNBR), hence why field-based metrics such as those in Fig. S3 are so valuable.

4.1.2. Wet sclerophyll forests

In wet forests, we saw similar effects to those apparent in dry forests, with both prescribed burning and shaded fuel breaks reducing overall fuel load. Prescribed burning reduced surface fuel loads but *increased* dead elevated fuel loads, whereas fuel breaks reduced elevated fuel loads, but did not affect surface fuels. The high degree of variation among untreated forests, however, meant that many of these differences we not statistically significant, highlighting the need for larger sample sizes to detect differences. Prescribed burning is uncommon in wet forests in the southeast of the continent (Wardell-Johnson et al., 2017), but case studies in the southwest and northeast of Australia indicate that the fuel reduction effect can sometimes be partially offset by the subsequent deposition of leaf litter from understorey trees (Furlaud and Bowman, 2020). Interestingly, the prescribed burns at our wet forest site had higher fire severity metrics than in our dry forest site (Supplementary Materials Fig. S3). Mechanical treatments, both in Australia and abroad, have been shown to reduce elevated fuel loads and stem density, but increase surface fuel load, due to residual surface fuels (often referred to as slash) being left in place (Johnston et al., 2021; Piqué and Domènech, 2018; Volkova and Weston, 2019). Most of these studies found thinning and burning was the most effective at reducing fuel loads, as this consumed the slash. The mechanical treatments in our study essentially emulated this, as they involved manual slash removal, which explains the unchanged surface fuel load.

4.2. Effect of treatments on understorey microclimate and fire danger

Mechanical treatments in dry forests and prescribed burning in wet forests reduced both the foliar cover and diversity of the understorey (Supplementary materials Table S3). We show that this understorey removal can significantly dry out the understorey microclimate, harmonising with previous research. Increased foliar cover (Burton et al., 2019; Cawson et al., 2017), and structural diversity (Kovács et al., 2017; Norris et al., 2012) in the understorey increases microclimate humidity and coolness, and hence increases resultant fuel moisture content (Brown et al., 2022; Cawson et al., 2017; Ray et al., 2010). We found, however, that the removal of the elevated fuels did not significantly affect our estimate of the sub-canopy Forest Fire Danger Index (FFDI), which integrates humidity, soil dryness, temperature and wind speed (Noble et al., 1980). By contrast, previous studies have found that understorey (or sub-canopy) FFDI varies between different forest types (Supplementary Materials Fig. S4; Little et al., 2012) and that complete canopy removal can result in substantive increases in subcanopy FFDI (Wilson et al., 2022). The lack of differences in sub-canopy FFDI may also reflect the fact that we used understorey temperature and humidity measurements to offset weather observations from a nearby meteorological station rather than taking direct weather measurements in the understorey. We expand on this in Section 4.4.

4.3. Effect of treatment on potential fire severity

All treatments in our study reduced subsequent potential fire severity, with mechanical thinning showing particular promise to reduce the likelihood of crown fire in long-unburnt dry forests. Prescribed burning is well-researched is Australia, and has been shown to capable of reducing fire severity in forests, however the net effect of this may be small (Hislop et al., 2020; Morgan et al., 2020; Penman et al., 2011). Mechanical treatments, on the other hand, are relatively poorly studied in the Australian context (Keenan et al., 2021). The few studies to have been conducted in Australian *Eucalyptus* forests focus on the removal of the entire understorey, including elevated fuels and the mid-storey. These studies have yielded conflicting conclusions, with some finding that thinning reduces subsequent modelled fire risk (Volkova et al., 2017; Volkova and Weston, 2019), and others finding that thinning has no effect on remotely-sensed wildfire severity (Taylor et al., 2021a; Taylor, Blanchard and Lindenmayer, 2021b). However, a large body of research covering mechanical treatments in North America has found thinning, often followed by prescribed burning, to be extremely effective at reducing fire risk (Kalies and Yocom Kent, 2016).

No previous empirical study, however, has explicitly investigated either the aforementioned fuel load-microclimate trade-off, or treatments that remove only the near-surface and elevated fuels. Rather, previous Australian studies have focused on fuel load reduction in mechanical treatments that remove the entire understorey (including the mid-storey). Importantly, we show that, though all our fuel reduction treatments increased understorey dryness, the magnitude of this effect is relatively minor in the context of fire behaviour, compared to the effect of reduced fuel load (Fig. 7). Furthermore, the different treatments did not substantially affect the number of days fuels were available to burn (Supplementary Materials Fig. S7). While there has been much discussion about the utility of mechanical treatments in reducing fire hazard reduction (Keenan et al., 2021; Ximenes et al., 2017), there have been concerns that mechanical thinning will dry out forest understoreys and hence increase fire risk (Little, 2020). For instance, modelling research indicating that a leaving residual mid-storey after thinning will maximise reductions in fire risk (Banerjee et al., 2020).

4.4. Study limitations

While this study makes important insights into the effects of fuel reduction treatments, there are several important limitations to our methods, reflecting necessary study design simplifications given time and resource limitations. First, our measurements of understorey microclimate did not capture the full complexities of fire danger dynamics. Wind speed and fuel moisture have been shown to be the primary predictors of fire behaviour (Sharples, 2022), yet we did not account for wind speed. Removing elevated fuels and opening the understorey would likely increase sub-canopy wind speed, as there is a link between forest structure and wind reduction (Moon et al., 2019), though the magnitude of the effect is unclear (Russell et al., 2018). We also did not measure gravimetric fine fuel moisture content (FFMC), rather we measured a fuel moisture proxy, Fuel Moisture Index (FMI), which has been shown to be a good predictor of FFMC (Bowman et al., 2022; Nyman et al., 2015; Sharples and McRae, 2011). Both were necessary simplifications, given the complexities of measuring wind speed (expensive weather stations are required), and FFMC (regular destructive sampling or expensive equipment is required), however we argue further research into the effects of fuel treatment on sub-canopy wind speed is necessary.

Second, we used a simplified mechanistic implementation of the McArthur model to estimate potential fire behaviour and associated fire severity in treated and untreated sites. The McArthur model forms the basis of the most widely used operational fire behaviour model in Australia (Phoenix Rapidfire). The McArthur equations, however, only consider total fuel load, not structure, and have been shown to underpredict rate of spread in some dry forests, and to overpredict flame height in wet forests (Furlaud, Prior, et al., 2021a; McCaw et al., 2008). More generally, it overestimates the importance of fuels, especially in extreme weather (Bradstock et al., 2009). Our mechanistic implementation of the McArthur model does loosely account for vertical structure and arrangement (it simulates ignition of the ladder fuels only if surface fire flame heights exceed the height to crown base of the elevated layer). However, the McArthur equations themselves (Eqs. (1) and (2)) only consider fuel load and not structure, so the nuances of ladder fuel combustion, when compared to that of leaf litter, cannot be accounted for. This likely partially explains why our study found minimal differences between mechanical thinning and prescribed burning, despite their different effects on fuel profile. Our choice of the McArthur model, however, was necessary given more recent, accurate models are either extremely data-intensive or require qualitative descriptions of fuels which make quantitative comparisons difficult (e.g. Gould et al., 2007; Zylstra et al., 2016).

Last, our study only investigated fuel treatment under a very specific set of conditions: the fuel treatments had occurred in the year before measurements, and the weather record we used for fire behaviour modelling was recorded during a year (2021–22) in which a La Niña climate mode, as opposed to an El Niño climate mode, was active, indicating lower than average fire weather danger. The El Niño-Southern Oscillation (ENSO) is the primary climatic driver of fire danger in southeast Australia, with stronger correlations between El Niño modes, hot, dry weather, and fire activity than with other southern hemisphere climate modes (Mariani et al., 2016). The effects of fuel treatment on moderating fire behaviour are strongest immediately after implementation, however there is disagreement as to how long the effect of reduced fire danger lasts (Fernandes and Botelho, 2003; Penman et al., 2011). This study does not attempt to answer that question, rather we focused on immediate differences between treatments. Further, there is broad consensus that fuel management becomes less effective in reducing fire behaviour in extreme weather (Bowman et al., 2016a; Bradstock et al., 2009). Continued monitoring of these treated forests is needed to understand how long the treatment effects last, and how effective they are under more severe weather.

4.5. Management and ecological implications

In this study, we show that mechanical treatments and low-intensity prescribed burning are similarly effective at moderating subsequent fire behaviour, even under moderate-high fire danger, in both dry sclerophyll forests and wet sclerophyll forests. In dry forests, predicted subsequent fire intensity after all three treatments was below the 10,000 kW m^{-2} threshold at which firefighting activities are considered safe. In wet forests flame heights were half as high after both treatments as they were in untreated forests. This indicates that all these treatments, when their implementation is practical, can re-introduce conditions conducive to intentional, low-severity fire into forests where fire regimes had been previously disrupted. A diverse array of mechanical treatments have been used to restore low-severity fire regimes to ecosystems across western North America (Hessburg et al., 2016; Schwilk et al., 2009). Our results suggest mechanical removal of elevated fuels have the capacity to do the same thing in Australia in these ecosystems. Importantly this will allow for the maintenance of the reduced fire risk through subsequent planned burning regimes, even under worsening weather conditions with climate change.

Given that the effects on subsequent fire behaviour are similar, decisions on which treatment to use should be based on human safety, costs, and ecological considerations. The benefits and drawbacks of prescribed burning are well documented in Australia (Penman et al., 2011). Prescribed burning can be effective when used as a localised, targeted management intervention, however when considered at the landscape scale, the benefits are relatively modest, especially in a changing climate (Clarke et al., 2022; Furlaud et al., 2018). Further, these benefits are often outweighed by the costs, such as the risk of escape and smoke impacts on public health (Borchers-Arriagada et al., 2021; Penman et al., 2020). That we found mechanical treatments to have a similar effect on fire behaviour as prescribed burning suggests that a similar dynamic may be true for mechanical treatments: they are likely to be most effective when used in a targeted, localised fashion. This is especially important given their high cost. However, this high cost may be offset by recovering the biomass removed for timber or energy (Hartsough et al., 2008). The ecology of each system must also be carefully considered when planning treatments. Our study systems had substantially disrupted fire regimes, dominated by *Allocasuarina* in dry forests or dense regrowth in wet forests, in which an intervention was needed. For example, prescribed burning can have negative effects on wildlife habitat and biodiversity in southern Australian ecosystems if the frequency or intensity is too high (Bradshaw et al., 2018; Catling et al., 2001). Similarly, thinning also can have positive or negative impacts on different wildlife species, depending on the ecosystem and treatment design (Converse et al., 2006). Therefore, a deep ecological understanding is necessary to design such interventions. It is important to note this was a point-based field study, not a landscape-scale study, on the effectiveness of different fuel treatments. When designing fuel treatments, however, effects need to be understood at the landscape scale: field and remote-sensing data need to be aggregated for a wholistic understanding of fire risk. This should include data such as remotely-sensed forest structure (LiDAR; Price and Gordon, 2016), fuel moisture (Yebra et al., 2013), productivity (NDVI/VSPI; Massetti et al., 2019), and historical fire severity (dNBR; Hislop et al., 2020).

Our study underlines the primary importance of fuel reduction in reducing fire risk and creating conditions for low-severity fire, hence we argue that there is need for a diverse array of management interventions that reduce understorey fuel load. Of utmost importance is the restoration of traditional Aboriginal landscape and cultural burning. Such burning has embedded within in it the aforementioned deep ecological knowledge which is necessary in the design of treatments (Fletcher et al., 2021). However, in the face of climate change, novel, and heterodox, interventions may be required as well. For example marsupial megafauna may have created openings in wet and dry forests affecting fire regimes and creating heterogeneity (Bowman et al., 2012; Bowman et al., 2016b), and animals such as grazing marsupials, browsing megafauna and domestic livestock could replicate this effect, as has been suggested for other ecosystems (Bowman, 2012; Donlan et al., 2006).

5. Conclusion

In this study we show that both prescribed fire and mechanical fuel removal have the capacity to restore low-severity fire regimes to two ecosystems whose regime has been disrupted. We show this by evaluating the trade-off between fuel removal and increased understorey dryness associated with these interventions. Our results indicate that, in the context of subsequent fire behaviour, the effect of fuel removal clearly outweighed the effect of a drier microclimate, and that, immediately following these treatments, requisite conditions are created for the re-introduction of low-severity fire. However, the longevity of these effects is not currently understood so further monitoring is needed. Our results underscore the importance of designing novel treatment techniques to reverse anthropogenic ecological changes in the face of climate change. In the context of fire regimes, this has already been widely implemented in North America and Europe, including through variable density thinning in the western US to restore fire regimes and habitat heterogeneity (Puettmann et al., 2016), the restoration of silvo-pastoral grazing of livestock in Mediterranean Europe to manage fuel loads (Robles, Ruiz-Mirazo, Ramos, González-, & Rebollar, 2009; Ruiz-Mirazo et al., 2011), and shaded fire breaks in densely populated areas of California (Agee et al., 2000). The treatments in this study only represent a starting point for southern Australian *Eucalyptus* forests. Both burning and mechanical techniques could be combined to develop novel treatments that further reduce fire risk. Such innovations are desperately needed given the rising global fire risk in the face of climate change.

Credit author statement

James M. Furlaud: Conceptualization, Data curation, Funding acquisition, Formal analysis, Investigation, Methodology, Project administration, Visualization, Writing – original draft, Writing – review & editing. Grant J. Williamson: Conceptualization, Methodology, Data Curation, Writing – review & editing. David M.J.S. Bowman:Conceptualization, Funding acquisition, Methodology, Supervision, Writing – original draft, Writing – review & editing.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2023.118301.

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