Australian Forestry

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/tfor20

Fuel weight and understorey hazard dynamics in mature karri (*Eucalyptus diversicolor*) forests in southwest Western Australia

N. Burrows, A. Wills & V. Densmore

To cite this article: N. Burrows, A. Wills & V. Densmore (11 Oct 2023): Fuel weight and understorey hazard dynamics in mature karri (*Eucalyptus diversicolor*) forests in southwest Western Australia, Australian Forestry, DOI: 10.1080/00049158.2023.2251249

To link to this article: https://doi.org/10.1080/00049158.2023.2251249

Published online: 11 Oct 2023.

AUSTRALIAN FORESTRY
https://doi.org/10.1080/00049158.2023.2251249

Taylor & Francis
Taylor & Francis Group

Fuel weight and understorey hazard dynamics in mature karri (*Eucalyptus diversicolor*) forests in southwest Western Australia

N. Burrows, A. Wills and V. Densmore

Department of Biodiversity, Conservation and Attractions, Manjimup, Western Australia, Australia

ABSTRACT

Fuel properties influence the behaviour of forest fires, so understanding how these change with time since fire is important for appraising the bushfire threat and planning and implementing bushfire mitigation operations. A space-for-time study in mature karri forests with fuel ages ranging from 1 to 92 years demonstrated that total fine-fuel weight (TFFW) increased with time since fire for about 30 years then plateaued at a mean value of about 50 t ha^{-1}. For fuels older than four years, on average, 74% of TFFW was in the surface fuel layer (the litterbed) and 17% was in the near-surface layer (up to 1 m above the surface layer). Live understorey vegetation contributed only about 6% to TFFW. Predicting TFFW from time since fire was improved by including karri tree basal area. Mean understorey height (U_{ht}) increased with time since fire, peaking at 6 m after about 30 years, then declining to about 4 m after 92 years. Mean understorey hazard (U_{haz}), derived from U_{ht} plus the proportion (%) of dead fuel in each fuel layer, followed a similar trend, peaking at 20–30 years post-fire, then declining. Although U_{haz} had declined by 36% from the maximum value by 60+ years post-fire, it was 27% higher than the U_{haz} value for young fuels (1–<5 years old). For a mean prescribed-burn interval of eight years, 50% of the forest fuel will be ≤four years old and so will be carrying about ⩽19 t ha^{-1} of fine fuel (≤38% of the maximum value), with a U_{haz} value of about ‹3.56 (<50% of the maximum value). Fuel weight and U_{haz} directly influence fire intensity, flame size, spotting potential and rate of spread. Therefore, prescribed burning, done strategically and at the appropriate temporal and spatial scales, will make bushfires less damaging and easier and safer to suppress.

KEY POLICY HIGHLIGHTS

- In karri forests, fine fuel weight accumulates for about 30 years post-fire and then plateaus. Understorey hazard (mean height of near-surface, elevated and aerial fuels weighted for cover and proportion of dead fuel) peaks at 20–30 years post-fire, then declines to about 64% of the maximum value in 60+-year-old fuels.
- Periodic (mean interval 8 years) low-intensity prescribed burning of karri forests will maintain fine-fuel weight at ⩽38% and understorey hazard at ‹50% of maximum values over 50% of the forest.
- Reducing fuel weight and understorey hazard by periodic prescribed burning will reduce rate of spread, fire intensity, flame dimensions and spotting potential, making bushfires easier and safer to suppress, and less damaging.

ARTICLE HISTORY
Received 28 December 2022
Accepted 31 July 2023

KEYWORDS
forest fuel dynamics; fuel weight; fuel hazard; fire management; prescribed burning; karri forest; *Eucalyptus diversicolour*

Introduction

Karri forests are tall open wet sclerophyll forests with karri (*Eucalyptus diversicolour* F.Muell.) as the dominant or co-dominant overstorey species (Ashton & Attiwill 1994). Restricted to the southwest of Western Australia, they mostly occur on red loamy soils in high-rainfall areas (1000–1300 mm annum^{-1}) and can occur as pure stands of karri or as karri in association with other eucalypts (Bradshaw 2015) (Figure 1). In mature forests, overstorey trees can reach heights in excess of 60 m; on some sites, sheoak (*Allocasuarina decussata* (Benth.) L.A.S.Johnson) and peppermint (*Agonis flexuosa* (Willd.) Sweet) occur as mid-canopy trees to 20 m. The karri forest region experiences a Mediterranean-type climate with warm dry summers and cool wet winters. Climate and accumulations of flammable vegetation have ensured that fire is an integral part of the ecology of these forests (Christensen & Abbott 1989; Burrows & Wardell-Johnson 2003). Details of the pre-European fire regime are unknown but included fires started by lightning and Noongar Aboriginal people (Hallam 1975; Underwood 1978). Since European colonisation, the region has experienced a diverse regime of high-intensity bushfires and low-intensity prescribed burns. High-intensity bushfires can kill overstorey trees, but complete stand replacement is uncommon in mature karri forests (Bradshaw and Rayner 1997; Etchells et al. 2020). Dominant understorey species, including netic (*Bossiaea aquifolium* Benth.), hazel (*Trymalium odoratissium* Lindl.) and karri wattle (*Acacia pentadenia* Lindl.), are readily killed by fire and regenerate prolifically post-fire from soil-stored seed (fire-promoted species). As these relatively short-lived (30–40 years) single-stemmed species age and grow taller, they shed leaves and twigs from the lower portions of their stems and decline in density (McCaw et al. 2002). In long-unburnt areas, scattered surviving plants of these species can reach heights in excess of 12 m.

CONTACT V. Densmore Valerie.Densmore@dbca.wa.gov.au Department of Biodiversity, Conservation and Attractions, Brain Street, Manjimup, Western Australia 6258, Australia

Figure 1. Four-year-old (left) and 26-year-old (right) karri forest (*Eucalyptus diversicolour*) fuels. Younger fuels are characterised by a light, dead, surface fuel layer, a light near-surface fuel layer (to 1 m) of live and dead material, and a dense live understorey that forms an elevated fuel layer to 3 m. Older fuels are characterised by heavy, dead surface and near-surface fuel layers, a sparse tall understorey (hazel and netic) making up the aerial fuel layer (to 14 m), and the increasing dominance of the persistent understorey shrub karri oak (*Chorileana quercifolia*) in the elevated fuel layer (to 3 m)

Fuel properties, including weight, composition, structure and moisture content, together with weather conditions and topography, affect the behaviour of a bushfire – its rate of spread, intensity, flame size and spotting potential (Sullivan et al. 2012). Fire behaviour determines a bushfire's environmental impacts, its potential to harm human communities, and its suppression difficulty (Alexander 2000; Stephenson et al. 2013; Filkov et al. 2020). Forest-fire managers need to be able to measure fuel characteristics and have a quantifiable understanding of how these change with time since fire to inform a range of policy, planning and operational decisions, including assessing bushfire threat and planning and implementing prescribed burns, and for bushfire suppression.

How live and dead vegetation is characterised as fuel depends on the fuel input requirements of fire-behaviour models and fire-danger rating systems appropriate to the fuel type. Empirically derived fire-behaviour models have been developed for southern Australian dry open eucalypt forests (McArthur 1962; Sneeuwjagt & Peet 1985; Cheney et al. 2012; Cruz et al. 2021). Early models described forest fuel solely in terms of weight per unit area (fuel weight) because, according to these models, this relates directly to rate of spread (McArthur 1962, 1967, 1973; Peet 1965, 1972; Luke & McArthur 1978; Sneeuwjagt & Peet 1985). However, based on laboratory and small-plot field experiments in jarrah forests, Burrows (1994, 1999a, 1999b) was unable to find a relationship between fine-fuel weight and head-fire rate of spread for wind-driven fires, although he reported a positive relationship for backing fires. McCaw et al. (2012) concluded that although rate of spread in dry eucalypt forests increased with fuel weight, it was more strongly correlated with other fuel structural characteristics. Cruz et al. (2021) and Cruz et al. (2022) reported that fuel weight directly affected rate of spread but that its influence declined with increasing severity of fire weather conditions. Fuel weight in eucalypt forests is correlated with fuel structural changes as fuels age, making it difficult to separate the influences of fuel weight, fuel age and fuel structure on rate of fire spread (McCaw et al. 2012). Although there is inconsistency in the literature about the role of fuel weight on rate of spread of forest fires across the range of burning conditions, the quantity of fuel that burns in the flaming zone directly affects fireline intensity and flame size (Byram 1959; Cheney 1990; Burrows 1999b; Alexander & Cruz 2019; Cruz et al. 2022). However, reliably measuring the weight of fuel that actually burns in the flaming zone of bushfires is problematic (Tangren 1976; Cruz et al. 2021). In laboratory fires, the proportion of eucalypt litterbed (surface fuel – SF) weight consumed in the flaming zone was approximately 65%, with a further approximately 15% consumed as smouldering combustion and approximately 20% being ash residue (Burrows 1994, 2001). In the field, the proportion (by weight) of SF burnt by the various stages of combustion is unknown but is likely to be highly variable, depending on factors such as fuel depth, bulk density and moisture content, and on weather conditions, especially wind speed. In the absence of field data for karri forests, we have assumed that all fine fuel is consumed in the flaming zone. The most recent dry eucalypt forest fire behaviour model (Vesta 2) (Cruz et al. 2021) incorporates both fuel weight and fuel structure as predictors of rate of spread, but the Australian bushfire fuel classification system (Hollis et al. 2015; Cruz, Gould et al. 2018) is based solely on vegetation/fuel structure.

Studies in southern Australian eucalypt forests typically report that dead fine fuel accumulates quickly after fire and then slows as the rate of accession approaches the rate of decomposition (Peet 1971; Birk and Simpson 1980; Raison et al. 1983; O'Connell 1989; Burrows 1994; Gould et al. 2011; Neumann et al. 2021). There have been three published studies of karri forest fuel-weight dynamics. One was the development of a mechanistic litter accumulation model (O'Connell 1987) and two were field studies of the litter (surface) fuel layer and the dead suspended (near-surface) fuel layer up to 1 m in young even-aged regrowth (McCaw et al. 1996, 2002). An unpublished study was carried out in mature karri forests in the early 1970s, the findings of which are summarised in table form in Sneeuwjagt and Peet (1985). Although these studies used different methodologies and were carried out in structurally different karri forests, they arrived at the same general conclusion – that the weight of dead fine fuel in karri forests could be best explained by the model first proposed by Olson (1963), as follows:

$$S_{tt} = S_{ss}(1\text{-}e^{-k.Age}),$$

where S_{tt} = fuel weight at time t, S_{ss} = steady-state fuel weight and k = the decomposition constant.

There are no published studies of the relationship between time since fire and fine-fuel weight for mature karri forests, which we define here as unlogged (virgin) forests or regrowth forests >80 years old. Likewise, there have been no studies of the changing structure and hazard of mature karri forest fuels consistent with the Australian bushfire fuel classification system (Hollis et al. 2015) or the Vesta 2 fire behaviour model. Therefore, this study had two primary objectives: (1) to model the fine-fuel weight dynamics of mature karri forests with time since fire; and (2) to characterise and quantify how fuel hazard, based on fuel structure, changes with time since fire. In short, this study aimed to answer the question, how do fuel weight and fuel hazard in mature karri forests change with time since fire?

Methods

Study sites

The study was carried out in mature karri forests with different but known fuel ages (time since fire) in the southwest of Western Australia (Figure 2). Fuel age, which ranged from 1 to 92 years, was derived from records held by the Department of Biodiversity, Conservation and Attractions, the agency responsible for fire management on public land in Western Australia, including national parks, in which most sample sites were located. Of the 72 sites assessed, 62 were last burnt by prescribed fire and four were last burnt by bushfire. The type of fire on six sites was unknown. For assessing fuels, at each site a 20 m line transect was established in the forest 30–40 m from the edge of the nearest road/track. The distance between sample sites of fuels of the same age was at least 50 m and in most cases considerably greater. Basal area (a measure of site occupancy) of overstorey and mid-canopy tree species was determined by measuring the diameter of live trees (at breast height over bark) within a 20 m radius circle, the centre of which was the mid-point of the line transect. Overstorey tree top height and height to the base of the overstorey tree canopy, and understorey shrub top height and height to the base of the understorey shrub canopy, were measured using a hypsometer laser range finder or a height stick (the latter for shrubs ≤2 m high). Fuel was classified following the methodology of Gould et al. (Gould, McCaw, Cheney, Ellis, Knight, Sullivan, 2007; Gould, McCaw, Cheney, Ellis, Matthews, 2007) which is consistent with the Australian bushfire fuel classification framework (Gould & Cruz 2012; Hollis et al. 2015; Cruz, Gould et al. 2018). The following fuel layers were measured: SF; near-surface fuel (NSF); elevated fuel (EF); aerial fuel (AF); and bark fuel (on live standing trees). Here, AF relates to tall live shrubs up to 14 m, which can form a distinct layer above the EFs. Gould et al. (Gould, McCaw, Cheney, Ellis, Knight, Sullivan, 2007) included 'intermediate' and 'overstorey' fuel layers, but this considers the bark-flammability characteristics of live trees. Being a smooth-barked species, the bark on karri trees is non-flammable, except at times when it is being shed in early summer. Rough-barked species such as marri (*Corymbia calophylla* (Lindl.) K.D.Hill & L.A.S.Johnson) and red tingle (*Eucalyptus jacksonii* Maiden) often grow with karri; where this was the case, the bark hazard of these species was rated following the methodology of Gould et al. (Gould, McCaw, Cheney, Ellis, Knight, Sullivan, 2007; Gould, McCaw, Cheney, Ellis, Matthews, 2007).

In the current study, 'fine fuels' are fuel elements likely to be consumed in the flaming zone of an intense bushfire and include dead leaves, bark, twigs and other dead woody material <6 mm thick (Burrows 2001), and live leaves and stem material <4 mm thick (Harmon et al. 2022). Definitions of the fuel layers used in the current study, and the measurements made, are as described below.

Surface fuel (up to 120 mm above the soil surface)

SF is dead fine fuel on the forest floor. A relationship between SF depth and oven-dry weight (t ha^{-1}) was established by measuring the depth and oven-dry weight of fuel harvested from a 0.049 m^2 circular sample area down to mineral earth. In total, 46 samples were taken across a range of fuel ages with the resulting relationship (Figure 4):

$$SF\ (t\ ha^{-1}) = 0.543(SF\ depth\ (mm)) - 0.0035\ (R^2 = 0.88)$$

This relationship was used to estimate mean SF weight at each site by measuring the depth of the SF layer at 2 m intervals along a 20 m line transect (10 measurements per site). Percent cover of SF was determined by recording its presence or absence at 1 m intervals along the transect.

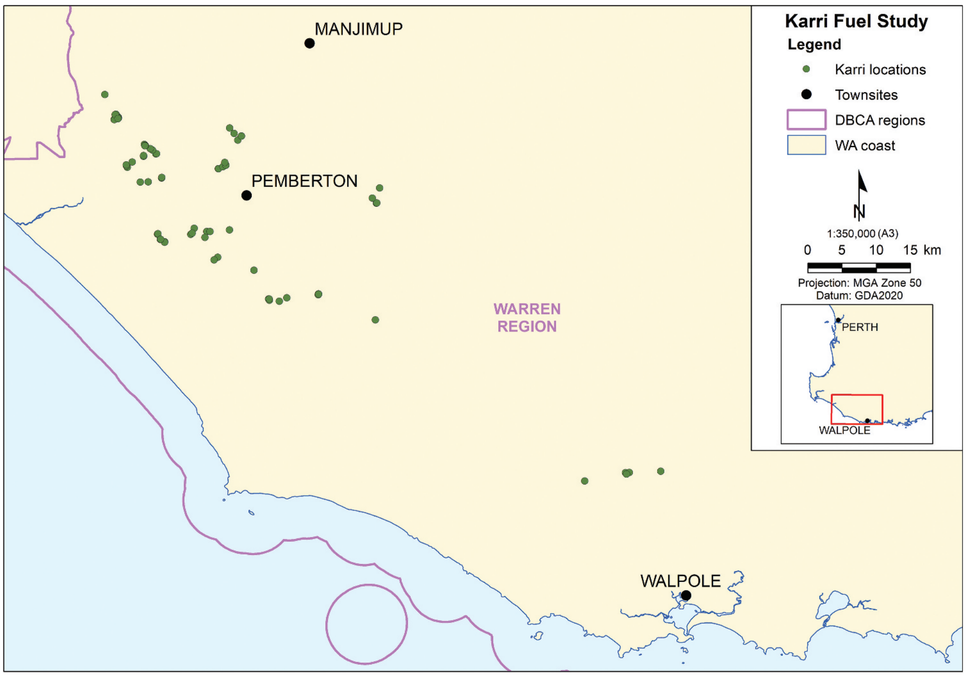

Figure 2. Location of 72 karri forest fuel study sample sites in southwest Western Australia

Near-surface fuel (up to 1 m above the SF)

NSF is fine live and dead fuel suspended above the SF to a height of 1 m. It is predominantly dead material, except in recently burnt forest (≤1-year-old), where small live shrubs dominate the layer. In older fuels, the live shrub canopy has grown beyond the NSF layer and into the EF layer. Mean NSF weight was measured by harvesting and weighing fuel from 1 m^2 quadrats placed at 4 m intervals along the 20 m transect (5 quadrats per site). Moisture content samples were taken to determine the oven-dry weight of the harvested fuel. Mean height and percent cover of NSF were estimated using the point intercept method. Presence or absence of NSF was recorded at points 1 m apart along the 20 m transects, and, if present (i.e. if there was NSF vertically above or below the point), its height was measured using a height stick. In one-year-old fuels, where the NSF comprised dense seedling regeneration to 1 m, the number and mean height of seedlings in each 1 m^2 quadrat was recorded.

Elevated fuel (up to 3 m above the near-surface fuel) and aerial fuel (up to 11 m above the elevated fuel)

EF and AF are predominantly fine fuels in live shrubs (fire-promoted species – hazel, netic and karri wattle) that dominate the understorey in the early and intermediate years post-fire. In fuels older than about 5–6 years, these layers separate, which is why we included an AF layer. A relationship between stem diameter and dry biomass was developed for live hazel and netic. Karri wattle was not included because it occurred infrequently at the study sites. Where it occurred, we assumed it had a similar stem diameter/biomass relationship to hazel and netic. In total, 30 netic and 29 hazel plants ranging in size and age were harvested, stem diameter at 1.3 m above ground was measured, and leaves and other live material <4 mm thick were stripped from each plant, oven-dried and weighed. A relationship between plant stem diameter and oven-dry fine-fuel weight (<4 mm) was developed. Mean shrub top height, mean height to shrub canopy base, and percent cover of EF were measured using the point intercept method, as described above for NSF. Height measurements determined how much of the shrub canopy was in the EF layer (1–3 m) and how much was in the AF layer (>3–14 m). The density of these understorey plants (netic, hazel and karri wattle) decreases significantly with time since fire (McCaw et al. 2002), so two sample methods were used to accommodate this: (1) stem diameter was measured for all live plants in a 40 m^2 belt quadrat (i.e. 1 m either side of the 20 m line transects); and (2) triangular tessellation, which involves measuring the length of the sides of the smallest triangle formed by three plants around a sample point (Ward 1991). The middle and each end of the 20 m line transects were used as triangular tessellation sample points and the stem diameter of each plant forming the triangles around these points was also measured. The highest density value derived from these procedures at a site was used in analysis. Mean plant density (stems ha^{-1}), mean stem diameter, mean top height and mean height to the base of the shrub canopy were used to estimate fuel weight (<4 mm thick) in tonnes per hectare in the EF and AF layers.

As fuels aged and the density of netic, hazel and karri wattle decreased, karri oak (*Chorilaena quercifolia* Endl.), a sparse, low, obscure understorey plant in the early post-fire years, increased in cover and height to become the dominant understorey species in older fuels (>approx. 11 years old) on most sites. In older fuels, it is a sprawling, bushy shrub to 3 m high and 2–3 m wide. Fuel weight (live leaves and stem material <4 mm thick) in karri oak clumps in older fuels was estimated by first determining mean clump fuel bulk density by harvesting and drying fine fuel from a 1 m^3 sample taken from the base of 23 clumps. Based on visual assessment, fuel bulk density was assumed to be uniform throughout the clump. Knowing the mean clump fine-fuel bulk density (0.34 kg m^{-3}; standard error = 0.011), fine-fuel weight (t ha^{-1}) was estimated by determining the mean height and cover of karri oak using the point intercept method described above.

Coarse woody fuel (>6 mm ≤100 mm diameter)

Dead stems and branches on the forest floor comprised coarse woody fuel (CWF). We limited the measurement of CWF to 100 mm diameter for two reasons: (1) the transect length (20 m) was too short to adequately measure sparse pieces of larger material (Hollis et al. 2011); and (2) because of their low combustion rates, large pieces contribute little to flaming zone combustion (Burrows 1994). Each intercepted piece of CWF was measured and placed into one of ten diameter classes – the smallest class being 6–10 mm, with subsequent classes at 10 mm intervals. The volume of CWF (m^3 ha^{-1}), by diameter size class, was estimated using the line intercept sampling technique (Van Wagner 1968; Marshal et al. 2003; Hollis et al. 2011) along the 20 m transects. Total weight (t ha^{-1}) in each diameter class was calculated using the class mid-point to calculate volume and a mean dry wood density of 640 kg m^{-3}, derived from drying and weighing 20 solid (not decomposed) cylindrical pieces of CWF of known volume. The weight of CWF likely to burn in the flaming zone was calculated using a rate-of-weight-loss model (Burrows 2001) and a flame residence time of 37 seconds (Wotton et al. 2011). The rate-of-weight-loss model was developed from laboratory studies using oven-dry fuel particles burning on a load cell under zero wind conditions and so likely underestimates the rate of weight loss of CWF burning in a bushfire under severe fire weather conditions. This model was used in the absence of an alternative.

Modelling fine-fuel weight

Based on earlier work (Raison et al. 1983; O'Connell 1987; Burrows 1994; McCaw et al. 2002), we explored Olson's (1963) equilibrium model for modelling SF weight and total fine-fuel weight (TFFW = the weight of fine fuel in all layers) from time since fire. We also explored the performance of a logarithmic model. O'Connell (1987) found that the dominant contribution to fine-fuel accumulation in karri forests is from overstorey trees. Of the variables measured in the current study, karri basal area was identified in a distance-based linear measures analysis (McArdle & Anderson 2001) as an important variable explaining variation in SF weight, which is the dominant component of TFFW. Karri basal area was included in models to predict SF and TFFW as a proxy for factors that deflect the trajectory from an 'average' Olson-type fuel accumulation curve for mature karri forests. These predictive models took the form: $S_{tt} = S_{ss}(1\text{-}e^{-k.\text{time since fire}}) + b$ (karri basal area) + c.

We approximated S_{ss} from McCaw et al. (2002) as a starting point, then alternatively and iteratively adjusted k (decay constant) and the S_{ss} parameters to maximise the adjusted R^2 value using the regression function in MS Excel. Second- and third-order polynomial models were fitted to the EF and AF data. The R^2 values of second- and third-order polynomials using Olson's base model were examined for possible model combinations that deviated from time since fire and karri basal area alone. Tests were run using the mcgv package in R (R Core Team 2020).

Fuel flammability, understorey height and understorey hazard

Fuel flammability and fuel hazard are often poorly differentiated and thus used interchangeably in the literature. In general, flammability relates to individual species rather than being a property of vegetation communities (Scarff and Westoby 2006), while fuel hazard describes the propensity for a vegetation community to burn. Fuel flammability epitomises the capacity of fuel to ignite and sustain combustion. Anderson (1970) classically defined flammability using three elements: (1) ignitability – the delay on ignition; (2) sustainability – the duration of combustion; and (3) combustibility – the mass loss rate. The chemical composition of fuel strongly influences these elements, as does fuel moisture content (Mutch 1970; Dickinson & Kirkpatrick 1985; Scarff and Westoby 2006; Saura-Mas et al. 2010). Oxygen availability is central to flammability; thus, fuel particle shape (e.g. Zylstra et al. 2016) and fuel arrangements that promote aeration (Dickinson and Kirkpatrick 1985; Dimitrakopoulos and Papaioannou 2001; Scarff & Westoby 2006; Varner et al. 2015) influence flammability at the level of individual leaves to whole-plant scale. Fuel hazard metrics centre around the arrangement of flammable fuels in a vegetation community rather than at the species-level scale. Arrangement is usually characterised according to the vertical and horizontal structure of the fuel (height, cover), its bulk density and the proportion of dead material (e.g. McCarthy et al. 1999; Hines et al. 2010; Gould et al. 2011). Unlike fuel flammability, fuel hazard does not consider fuel moisture content, particle size, shape or chemistry; rather, fuel hazard scores aim to compare potential fire behaviour between vegetation communities that have similar species-level flammabilities but vary in fuel arrangement. For a given fuel or vegetation type, the greatest variability in fuel hazard is due primarily to variability in fuel structure (height, cover) and proportion of dead fine material, which responds more rapidly to environmental moisture fluctuations than fine live material (Rossa & Fernandes 2017). The current study did not measure fuel flammability (as defined above) but focused on measuring fuel hazard (as defined above). This is because, for a broad fuel type such as karri forest, the particle size, shape and chemistry of the fuel elements are more-or-less constant, with variability in fuel hazard primarily due to variability in structure (height, cover) and composition (proportion of dead material). There are no published fuel hazard assessment methods for tall wet eucalypt forests such as karri (Cawson et al. 2020). The original Vesta fire behaviour model for dry eucalypt forests used a fuel hazard score, being a numeric value (0–4) based on a visual assessment of the height, cover and proportion of dead material in the various fuel layers (Gould, McCaw, Cheney, Ellis, Matthews, 2007; Gould, McCaw, Cheney 2011). However, the more recent version of Vesta (Vesta 2) (Cruz et al. 2021) uses fine-fuel weight and mean understorey height (U_{ht}) to predict rate of spread, where:

Mean understorey height (U_{ht}) = *(mean height of the near-surface layer × cover) + (mean height of the elevated layer × cover).*

Following this protocol, we calculated a second mean U_{ht} measure for karri forests, which includes the aerial layer:

Mean understorey height for karri forests (U_{htK}) = *(mean height of the near-surface layer × cover) + (mean height of the elevated layer × cover) + (mean height of aerial layer × cover).*

Vesta 2 fuel input does not account for the proportion of dead material in the fuel layers; so, in addition to calculating mean U_{ht} and U_{htK}, we calculated a measure of mean understorey hazard (U_{haz}), being an additive function of mean U_{htK} plus the proportion of dead material (dp) in the near-surface (ns), elevated (el) and aerial (ae) fuel layers, as follows:

Mean understorey hazard $(U_{haz}) = ((ht_{ns} \times cv_{ns}) + dp_{ns})) + ((ht_{el} \times cv_{el}) + dp_{el}) + ((ht_{ae} \times cv_{ae}) + dp_{ae}))$.

While height and cover were measured along 20 m transects (described above), the proportion of dead material (by volume) within a 10 m radius of the centre of the line was estimated visually for each fuel layer. We assessed bark hazard following the Vesta protocol but, because the sites were mostly dominated by karri, a smooth-barked species that sheds its bark annually, site bark hazard was consistently rated as low or moderate and was not used in analysis. Strips of shed bark were mostly incorporated into the SF and NSF layers; in older fuels, some bark was suspended in the EFs and AFs.

Results

In total, 72 sites were sampled in mature karri forests in 26 fuel ages ranging from 1 to 92 years since fire. Of these sites, 26 were pure karri, 44 were mixed karri – marri, and two sites were mixed karri – red tingle. Structural characteristics of the forests sampled are

Table 1. Summary of overstorey tree structure of mature karri forests that were part of the fuel study

Tree top height (m)		Height to base of tree canopy (m)		Tree basal area (m^2 ha^{-1})		Canopy cover (%)		Stocking (stems ha^{-1})	
Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range
50	45–56	34	30–40	44	10–107	63	40–90	120	24–350

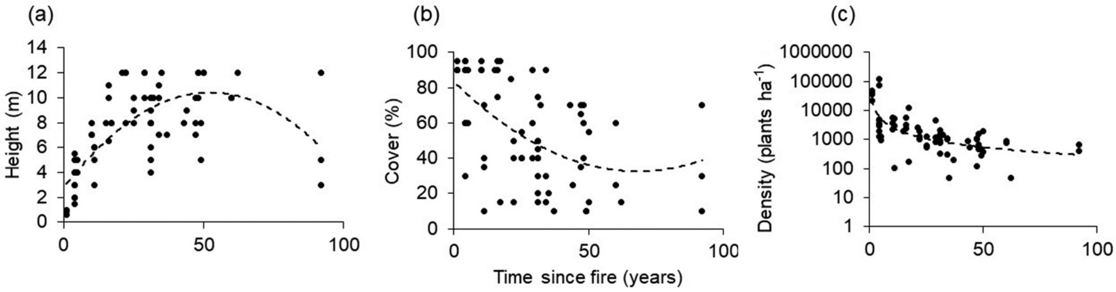

Figure 3. The relationship between live understorey (netic, hazel and karri wattle) height (a), cover (b) and density (c) with time since fire in mature karri forests. Dotted lines are best-fit trend lines

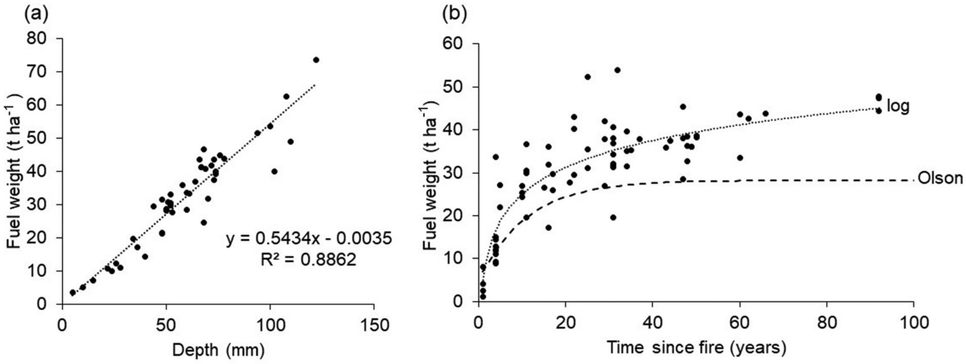

Figure 4. Relationship between karri forest surface fuel (SF) weight and depth (a), and SF weight and time since fire (b). The logarithmic model was a slightly better fit than the Olson model based on R^2 values (see Table 2)

summarised in Table 1. Stimulated to regenerate by fire from soil-stored seed, cohorts of hazel and netic occurred as understorey species on 92% of sites, and karri wattle occurred on 10% of sites. These species increased in height with time since fire but decreased in density (number of plants ha^{-1}) and cover due to competition and natural senescence (thinning) (Figure 3). In older fuels, the understorey dynamic was more complex, with plants ranging in size and therefore age, which partially explains the high variability in stem diameter and height for a given time since fire (Figure 3). Karri oak was present on most (82%) sites but, in the early years post-fire, it was a small, inconspicuous plant occupying <10% of the understorey cover. After about 11 years post-fire, the cover and height of karri oak increased with increasing fuel age, commensurate with a decrease in the density of hazel, netic and karri wattle. On sites with a fuel age >11 years, the mean cover of karri oak was 40% (range 10 –70%), and its height ranged from 1.8 m to 3 m. Several long-unburnt sites with high basal areas of sheoak were virtually devoid of live understorey.

Surface fuel weight

The relationship between SF depth and weight is shown in Figure 4a. The mean bulk density of the SF layer was 53.4 kg m^{-3} and SF weight ranged from 1.1 t ha^{-1} (a 1-year-old site) to 52.3 t ha^{-1} (a 25-year-old site). The relationship between SF weight (t ha^{-1}) and time since fire (years) is plotted in Figure 4b. We tested the conventional Olson model and a logarithmic model (Figure 4b) based on R^2 values, with the logarithmic model having a slightly better fit (Table 2). Predicting SF weight was improved by incorporating karri basal area (m^2 ha^{-1}) (Table 2). SF cover was 100% on all sites except on one of the one-year-old sites, which had a cover of 80%.

Table 2. Logarithmic, Olson and polynomial models for predicting surface fuel weight (SFW – t ha^{-1}), near-surface fuel weight (NSFW – t ha^{-1}), total fine-fuel weight (TFFW – t ha^{-1}) and surface fuel depth (SFD – mm) in mature karri forests from time since fire (TSF – years), karri basal area (KBA – m^2 ha^{-1}) and sheoak basal area (SBA – m^2 ha^{-1}). from model 8, it can be seen that the steady-state TFFW is 49.7 t ha^{-1} and the decay constant (k) is 0.12 for a mean karri basal area of 35.5 m^2 ha^{-1}

Model	Model type	Adjusted R^2
1. SFW = 5.91 ln(TSF) + 5.44	Log	0.74
2. SFW = 23.35(1-exp(−0.09(TSF)) + 4.89	Olson	0.73
3. SFW = 5.91 ln(TSF) + 0.09(TSF) + 3.3	Log	0.78
4. SFW = 23.35(1-exp(TSF)) + 0.07(KBA) + 4.07	Olson	0.76
5. NSFW = 1.91 ln(TSF) + 1.58	Log	0.33
NSFW = 0.00007(TSF)^3 + −0.0095(TSF)^2 + 0.439(TSF) + 0.027(KBA) + −0.114(SBA) + 1.190	Polynomial	0.50
6. TFFW = 11.62ln(TSF) + 6.86	Log	0.72
7. TFFW = 49.14(1-exp(−0.12TSF) + 1.058	Olson	0.74
8. TFFW = 49.38(1-exp(−0.12(TSF)) −0.013(KBA) + 1.06	Olson	0.74
9. SFD = 17.12ln(TSF) + KBA −1.35	Log	0.80

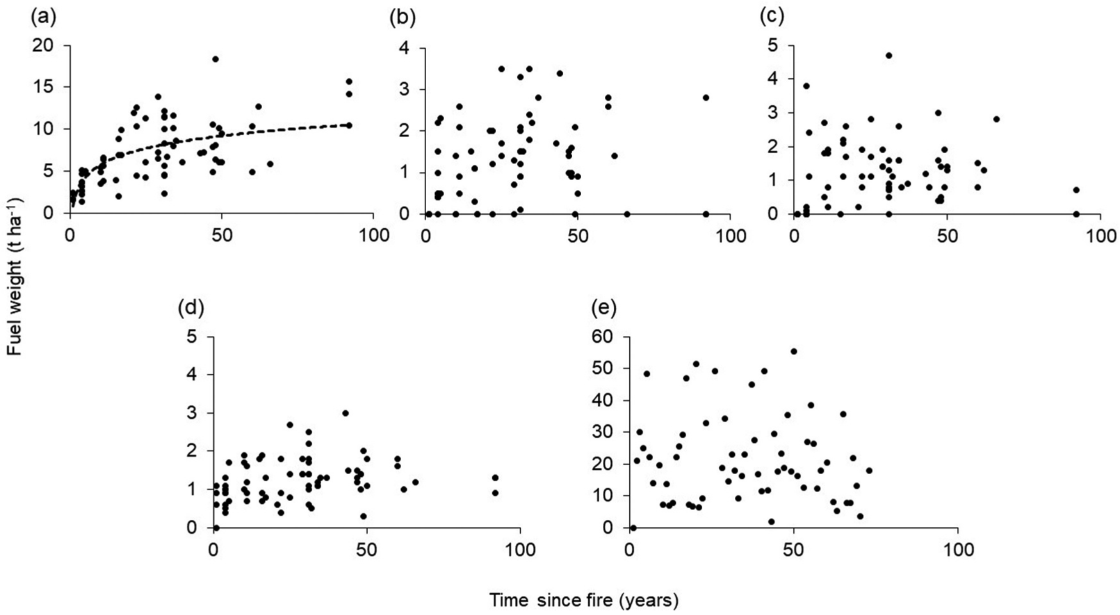

Figure 5. Relationship between karri forest near-surface fuel weight (a); elevated fuel weight (b); aerial fuel weight (c); weight of coarse woody fuel (CWF) available to burn in the flaming zone (d); and total weight of CWF (6–100 mm diameter) (e) with time since fire. Trend lines shown for data with better R^2 values (>0.4)

Near-surface fuel weight

In one-year-old fuels, 80–90% (by volume – visual estimate) of the NSF was low, live understorey shrubs that had regenerated in response to fire. By five years post-fire, 70–100% of the NSF was dead material because the fine fuel in live understorey shrubs had grown beyond the NSF layer and into the EF and AF layers. The mean bulk density of the NSF layer was 1.42 kg m^{-3}, ranging from 0.1 kg m^{-3} to 3.2 kg m^{-3}. The weight of NSF increased relatively quickly with time since fire to about 30 years, after which the rate of increase slowed. As evident in Figure 5a, there was significant variability, indicating that factors other than time since fire were affecting NSF weight. Of the other factors measured, basal area of sheoak and basal area of karri were statistically the next most important (Table 2).

Elevated fuel weight

EF predominately comprised fine components of live understorey shrubs. There was no EF in one-year-old fuels because the understorey was insufficiently developed. Up to about 11 years post-fire, EF mostly comprised live material (<4 mm thick) of netic, hazel and occasionally karri wattle, but as these species reduced in density with increasing fuel age, live karri oak became the dominant EF. Mean EF weight was 1.6 t ha^{-1}, ranging from 0.3 t ha^{-1} to 3.5 t ha^{-1}. Mean cover was 42.2% (range 10–80%) and mean height above the SF layer was 2.3 m (range 1.3–3 m). Mean bulk density of the EF layer was 0.07 kg m^{-3} (range 0.05–0.15 kg m^{-3}). Because of the seral succession of the understorey and the variability in cover of EF, fuel weight was only weakly related to time since fire (Figure 5b).

Aerial-fuel weight

There was little or no (depending on age) AF in the first four years post-fire because the understorey was insufficiently developed. Mean AF weight was 0.5 t ha^{-1} for fuels ≤five years and 1.3 t ha^{-1} for fuels >five years. As with EF, the weight of the AF layer was weakly related to time since fire (Figure 5c). There was little or no dead fuel in the AF layer.

Coarse-woody-fuel weight

The weight of CWF available to burn in the flaming zone was weakly related to time since fire (Figure 5d), but the total weight of CWF (6–100 mm diameter) was unrelated to time since fire (Figure 5e).

Total fine-fuel weight

TFFW is the weight of all fine-fuel elements that can potentially burn in the flaming zone and comprises dead fuel (<6 mm thick) and live fuel (<4 mm thick) in all fuel layers and varying fractions of CWF, depending on its diameter. TFFW ranged from a minimum of 4.0 t ha^{-1} at a one-year-old site to a maximum of 68.1 t ha^{-1} at a 25-year-old site. The mean TFFW in the oldest fuel measured here, 92-year-old fuel in Big Brook forest with a mean tree basal area of 46 m^2 ha^{-1}, was 57.9 t ha^{-1}. TFFW (t ha^{-1}) is plotted with time since fire (years) in Figure 6. The Olson modelled relationship between TFFW and time since fire was slightly better than the logarithmic relationship (based on R^2 values – Table 2). Mean TFFW plateaued at about 50 t ha^{-1} after about 30 years post-fire. For the mean karri basal area (35.5 m^2 ha^{-1}), the steady-state TFFW was 49.4 t ha^{-1} and the k (decomposition constant) was 0.12 (Table 2).

From O'Connell's (1987) finding that karri makes the dominant contribution to fine-fuel accumulation and given the variability of karri site occupancy as represented by its basal area, we derived a model from the base time-since-fire equilibrium (aka Olson) model adding karri basal area weighted by a multiplier that minimised the associated AIC value (Table 2). This improved the predictive capacity of the model. Because of the dominance of karri on the sample sites, including the basal area of other tree species did not improve the model (Table 3). With the exception of one-year-old fuels, SF

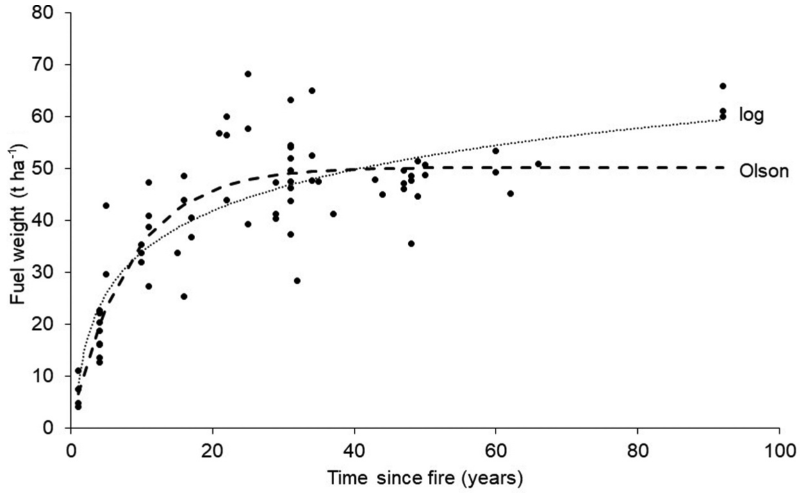

Figure 6. Total fine fuel weight with time since fire. The Olson model was a slightly better fit than the logarithmic (log) model based on R^2 values (see Table 2)

Table 3. Marginal tests for the proportion of variation explained in the Euclidean similarity matrix of fine-fuel loads using the primer DISTLM function

Variable	SS (trace)	Pseudo-F	*P*-value	Proportion of variation
Ln (TSF)	52.551	199.39	.0001	.74
Karri BA	9.2626	1.502	.002	.13
Marri BA	2.0997	2.1332	.15	.03
Sheoak BA	3.2354	3.3421	.08	.05
Peppermint BA	0.73948	.7367	.38	.01

BA = basal area (m2 ha-1); SS = steady state; TSF = time since fire (years).

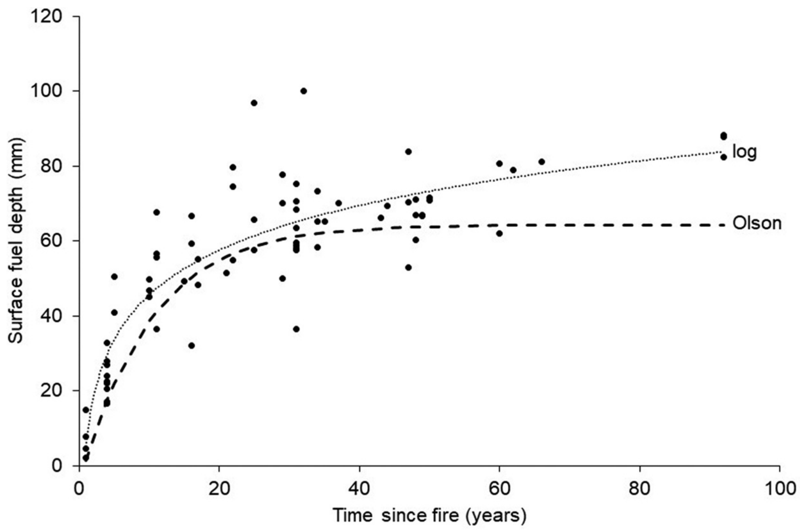

Figure 7. Karri forest surface fuel depth with time since fire. There was little difference between the Olson and logarithmic models based on R^2 values (see Table 2)

contributed most to TFFW. Averaged across all sites, the contributions of fuel layers to TFFW was: SF = 73.8%; NSF = 17.3%; EF = 3.0%; AF = 2.8%; and CWF = 3.1%.

Fuel structure

The relationship between SF depth and time since fire is shown in Figure 7. There was little difference between the logarithmic and Olson equilibrium models based on R^2 values. For a mean karri basal area (35.5 m^2 ha^{-1}), SF depth plateaued at about 70 mm after about 30 years. NSF height and cover showed a similar trend to SF of increasing with time since fire for the first 30 years or so and then plateauing, but the relationship was considerably more variable, reflecting local variability in karri basal area and understorey shrub structure (Figures 8a,b). In the early years post-fire (<4 years), the NSF layer was dominated by live shrubs that had regenerated in response to the fire, but, for older fuels, the proportion of dead material was mostly 80–90% (Figure 8c). EF comprised predominantly live vegetation. There was a weak relationship between the height and cover of this layer and time since fire, with the trend being a rapid increase in height in the first four years post-fire and then stabilisation at 2–3 m (mean 1.9 m) (Figures 8d,e). On eight sites, there was no EF. As discussed above, in the early years post-fire (≤11 years), the EF layer comprised hazel, netic and/or karri wattle, but, as the density of these species decreased and plants grew taller with age, the elevated layer was dominated by the persistent karri oak. The mean height of the AF layer (Figure 9a) was variable but generally increased with time since fire for the first 30

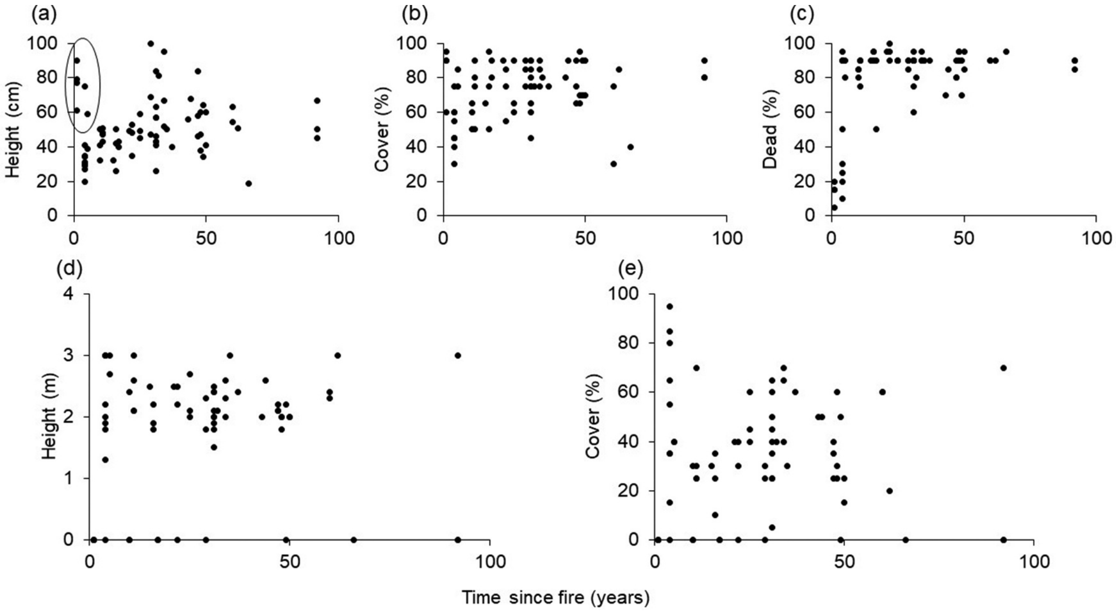

Figure 8. Karri forest near-surface fuel (NSF) height (a), cover (b) and proportion (%) dead (c) with time since fire. 'Circled' (a) are young fuels with live shrubs making up the NSF layer. Karri forest elevated fuel (1–3 m) height (d) and cover (e) with time since fire

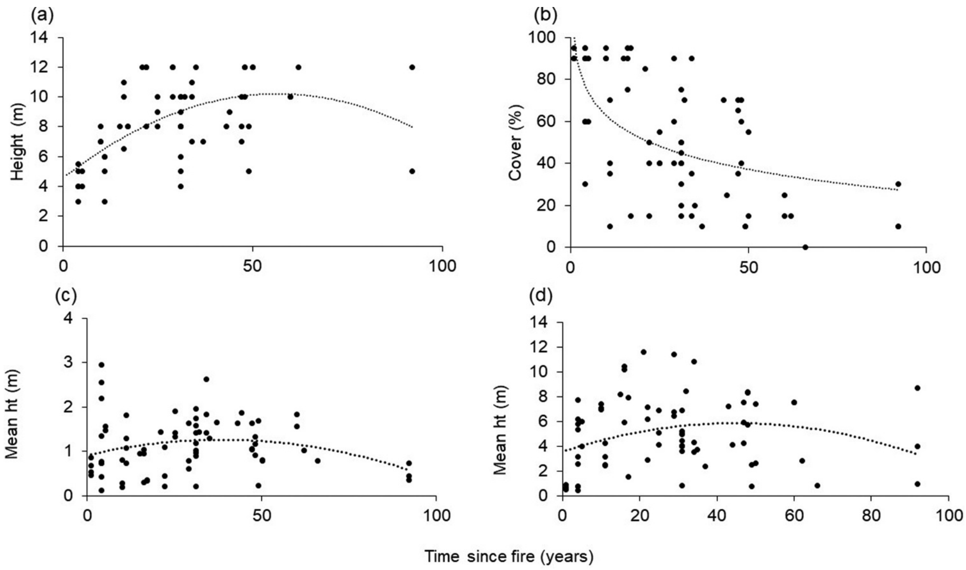

Figure 9. Karri forest aerial fuel height (a) and cover (b) with time since fire, and trends in understorey fuel height, weighted for cover, with time since fire for near-surface + elevated fuels (U_{ht}) (c) and near-surface + elevated + aerial fuels (U_{htK}) (d) ht = height

years or so, after which it more-or-less plateaued. Cover of AF was also variable but decreased with time since fire (Figure 9b). The high variability in height and cover of AF with time since fire is largely for the same reasons as given above for the variability in EF.

Understorey height and 'hazard'

Post-fire trends in mean understorey height calculated from NSF and EF (U_{ht}) (Vesta 2, Cruz et al. 2021), and for mean understorey height, including AF (U_{htK}), are show in Figure 9c, d. There is a high level of variability, but the trend is for an increase in both measures in the first 30 years or so post-fire and then a decline as the understorey thins. The post-fire trend in mean U_{haz}, being U_{htK} + the proportion of dead fuel in each layer (see definition above), is shown by fuel age classes in Figure 10. The trend approximates a parabolic curve, with the 'focus', or maximum mean U_{htK}, being in the 20–<30-year-old fuel age class. The highest individual site U_{htK} value was 12.8 in a 21-year-old fuel and the lowest was 0.4 in a one-year-old fuel. The mean U_{htK} for the 92-year-old fuel sites was 4.2.

Discussion

Fine-fuel weight

It is well established that fine-fuel weight in eucalypt forests is a function of time since fire and other complex biotic and abiotic factors that drive plant biomass productivity and

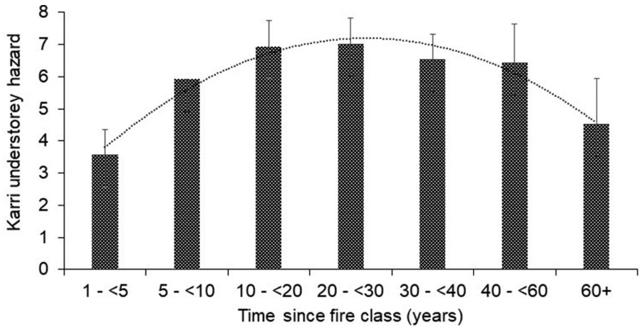

Figure 10. Karri forest understorey hazard (U_{haz}) derived from the mean understorey height of the near-surface + elevated + aerial fuel layers weighted for cover (U_{htK}), plus the proportion of dead fuel in each layer, with time-since-fire age classes. Standard error bars shown except where insufficient data were available

decomposition, including overstorey and understorey composition and structure, soil type, landform and climate (Duff et al. 2017; Jenkins et al. 2020; Neumann et al. 2021). In some forest types, fire history, especially fire severity, can also affect post-fire fuel properties (Collins et al. 2021). The severity of the antecedent fires at the study sites reported here is unknown, but, because most were prescribed burns, we assume that the fires were of low to moderate intensity and low severity. TFFW, or the weight of fuel potentially consumed in the flaming zone, was dominated by the weight of fuel in the SF layer (73.8% of total) and, to a lesser extent, the NSF layer, which together contributed 90% of TFFW. This is consistent with Cruz et al. (2021), who reported that litter (SF) in dry eucalypt forests accounted for 72% of fine-fuel weight. The contribution of live understorey vegetation (in the EF and AF layers) to the TFFW was very small (mean across all sites = 5.9%), which is consistent with the findings of O'Connell (1987). Therefore, the energy to drive bushfire behaviour is derived primarily from the combustion of dead fine fuels in the SF and NSF layers. Because of its dominant biomass, this fuel type also strongly influences overall fuel moisture content and hence fuel flammability and fire behaviour. Notwithstanding the temporal and spatial variability, and the complexity of fuel accession and decomposition, most of the variability in TFFW in mature karri forests was explained by time since fire and karri basal area, which is unsurprising because the bulk of the fine fuels in eucalypt forests are leaves, twigs, bark and floral parts shed from trees (O'Connell 1987; Burrows 1994; McCaw et al. 2002; Gould et al. 2011; Neumann et al. 2021). In mature forests, karri basal area may reflect site qualities that impinge on fuel accumulation and decay rates, as well as directly affecting fuel accumulation rates through the input of fuels and by altering the conditions such as microclimate that affect decay rates (e.g. Keane 2008; Thomas et al. 2014; Neumann et al. 2021).

TFFW accumulates rapidly in the first 15–20 years post-fire, with the rate of accumulation slowing thereafter. By about 30 years, influenced by the dynamics of the SF layer, TFFW more-or-less plateaus, following Olson's (1963) general equilibrium model form and as reported by others (e.g. Birk & Simpson 1980; Raison et al. 1983; O'Connell 1989; Burrows 1994; McCaw et al. 2002). The mean steady-state TFFW value of 49.7 t ha^{-1} reported here for mature karri forests is slightly lower than the value reported by McCaw et al. (2002) for 'leaf litter and twigs' (54.2 t ha^{-1}) in young even-aged karri regrowth stands but is considerably lower than what they reported for total dead-fuel weight (64.03 t ha^{-1}). The decay constant (k) of 0.12 $year^{-1}$ reported here is higher than that reported by McCaw et al. (2002) for total dead fuels (0.04 y^{-1}). The differences could be due to differences in tree and understorey growth dynamics between young even-aged regrowth stands and mature forests, hence differences in the composition of the SF and NSF layers. In young regrowth forests, trees are in a dynamic growth stage, which includes self-thinning of slower-growing suppressed trees and shrubs and high levels of twig and branch shedding. Also, McCaw et al. (2002) included woody material <25 mm thick, whereas in the current study we limited our modelling to dead material <6 mm thick.

Fuel structure, understorey height and understorey hazard

Forest fuel structure, or the spatial arrangement of live and dead vegetation, influences fire behaviour, especially rate of spread (McCarthy et al. 1999; Cheney et al. 2012; Zylstra et al. 2016; Cruz et al. 2021). A feature of the results presented here is the high localised variability of the fuel structural variables, such as height and cover, especially in the EF and AF layers dominated by live shrubs. Although these variables showed a weak relationship with time since fire and tree basal area, other factors have likely contributed to this variability, including the uneven-aged understorey in older fuels resulting from episodic inter-fire shrub regeneration, the fine-scale clumped distribution of hazel, netic and karri wattle, and the expansion of the persistent karri oak in older fuels as the other fire-promoted shrub species declined. Where it occurred as thickets, usually in older fuels, sheoak suppressed the development of understorey shrubs. This raises the issue of appropriate methodologies and scales at which to measure and map patchy forest fuels, especially the more variable, shrub-dominated EF and AF layers. Emerging techniques such as remote sensing and the modelling of vegetation types/fuel types based on environmental gradients, with ground validation, may provide more accurate measures of landscape-scale fuel hazard mapping (e.g. Arroyo et al. 2008; Jenkins et al. 2020).

With advances in forest fire behaviour science, there has been a move away from traditional models that use fuel weight as the sole fuel input to correlating measures of 'fuel hazard' or fuel height with fire rate of spread (Cheney et al. 2012; DENR 2012; Cruz et al. 2021). Although they reported a weak but statistically significant relationship between fuel weight and rate of spread, Cheney et al. (2012) and McCaw et al. (2012) found that the structure of the SF and NSF layers were most important in determining rate of spread in dry eucalypt forest. Cruz et al. (2021) report that fine-fuel weight in the SF and NSF layers has a significant effect on rate of spread for low-to-moderate-intensity fires; that fuel weight and understorey height, weighted by cover, have a significant effect on rate of spread of moderate-intensity fires; but that no physical fuel properties had a significant effect on rate of spread of high-intensity fires. Others suggest that, in addition to the spatial arrangement of fine fuels, species composition and associated plant traits such as leaf morphology and chemical composition can explain fuel flammability and fire behaviour (Mutch 1970; Gill & Zylstra 2005; Zylstra et al. 2016; Tumino et al. 2019). Measures of karri forest mean U_{htK} and mean U_{haz} developed in the current study increased post-fire as the understorey vegetation regenerated, peaked at about 20–30 years, and then declined to about 64% of peak values as the understorey vegetation senesced and thinned. Notwithstanding variability due to understorey dynamics and other factors discussed above, U_{htK} and U_{haz} show promise as meaningful measures of karri forest understorey fuel hazard. Further work is needed to evaluate whether these measures can be used in existing eucalypt fire behaviour models such as Vesta 2 to predict fire rate of spread in tall wet forests such as karri.

It has been proposed (e.g. Zylstra et al. 2016; Zylstra 2017, 2018) that, in tall wet forests such as karri, where the height and cover of the fire-promoted understorey declines (thins) with time since fire, introducing fire at regular intervals increases the 'flammability' of the forest because it maintains a dense live understorey. According to a fuel flammability model (Zylstra et al. 2016), flammability and hence fire behaviour is a function of the plant species present and the gaps between the plants. Further, the authors suggest that large flames only occur when live plants ignite and that fuel weight is unimportant (Zylstra et al. 2016). In contrast, some authors (e.g. Fernandes & Cruz 2012; Varner et al. 2015) assert that 'flammability' is a broad, loosely defined concept that does not necessarily translate to full-scale fire behaviour. Based on extensive field sampling in mature karri forests, we have demonstrated that mean U_{haz}, a measure that integrates NSF, SF and AF height, cover and the proportion of dead material, increases for about 20–30 years post-fire, reaching a mean peak value of 7.02, and then declines to 4.53 by 60+ years post-fire, or about 64% of the peak value. The mean U_{haz} for young fuels (1–<5 years old) was 3.56, or about 50% of the mean peak value. In summary, a karri forest landscape that is regularly prescribed burnt is less hazardous than one from which fire has been excluded because of the areal proportion of young fuels.

Conclusions and management implications

Although fine-fuel weight influences the rate of spread of low-to-moderate-intensity forest fires (Cruz et al. 2021), there is limited evidence that it has a significant influence on the rate of spread of fires burning under extreme fire weather conditions. Empirically derived dry eucalypt forest fire behaviour models (Cheney et al. 2012; Cruz et al. 2021) demonstrate the importance of fuel structure on rate of spread. There is growing evidence that, under severe fuel and fire weather conditions (dry fuels and hot, dry, windy weather), fuel properties such as fuel weight and structure have a reduced effect on rate of spread as fires become 'weather-dominated' (Bradstock et al. 2010; Tolhurst and McCarthy 2016; Cruz et al. 2022). However, *ceteris paribus*, total available fuel weight, which in mature karri forests peaks at about 30 years post-fire and then plateaus, can have a significant effect on fireline intensity, flame dimensions and spotting potential across all fire-weather conditions (Byram 1959; Burrows 1994; McCaw et al. 2012; Cruz, Sullivan et al. 2018; Cruz et al. 2022). Byram's (1959) measure of fireline intensity, which is a function of the weight of fuel consumed in the flaming zone, rate of fire spread and the calorific value of the fuel, remains the most useful single measure of a fire's damage potential and suppression difficulty; the suppression difficulty index (Thompson et al. 2018; Silva et al. 2020) is directly proportional to fire intensity (Alexander 1982; Cheney 1990; Sneeuwjagt et al. 2013; Wotton et al. 2017; Alexander and Cruz 2019; Cruz et al. 2022).

If it were possible to exclude fire from karri forests (beyond small scientific reference areas), TFFW would be maintained at its maximum level (mean about 50 t ha^{-1}) and mean U_{haz} would be at about 64% of its maximum level. Excluding fire from the karri forest for 60+ years to allow the U_{haz} level to fall to a level similar to young fuels would be a risky strategy that would likely result in a cycle of large, damaging bushfires. Alternatively, for a mean prescribed-burn interval of eight years (an operationally feasible objective), 50% of the forest fuel will be ≤four years at any point in time; thus, 50% of the forest will be carrying ⩽19 t ha^{-1} of fuel (≥62% below the maximum value – Figure 6) and have a U_{haz} condition of < 3.56 (≥50% below the maximum value – Figure 10). Reducing the interval between low-intensity fires will increase the area of low fuel weight and low $U_{haz.}$ We note that, although fuel management is an important fire management objective, there may need to be trade-offs in fire interval to accommodate other forest management objectives and values.

The broad spectrum of benefits of regular landscape prescribed burning at appropriate temporal and spatial scales for community protection, bushfire suppression, firefighter safety and forest health have been documented elsewhere (e.g. Underwood et al. 1985; Fernandes & Botelho 2003; Jurskis 2005; Turner et al. 2008; Burrows & McCaw 2013; McCaw 2013; Sneeuwjagt et al. 2013; Fernandes 2015; Plucinski 2019; Hislop et al. 2020; Morgan et al. 2020; Cruz et al. 2022). The challenge for forest-fire managers is to maintain an effective landscape prescribed-burning program given constraints such as limited resources, air-quality issues, and changing windows of opportunity associated with climate variability.

Acknowledgments

We thank the many people, too many to mention by name, who generously donated their time to assist with fieldwork. They include volunteers from the Bushfire Front and the Western Australian Department of Fire and Emergency Services. We thank Rick Sneeuwjagt and Lachie McCaw for advice on fuel sampling methods and Stefan de Haan, Shane French and Vicky Reynen (Western Australian Department of Biodiversity, Conservation and Attractions) for providing fuel-age data and preparing the sample-site map (Figure 2). We also thank Lachie McCaw, Phil Cheney, Miguel Cruz and two anonymous reviewers for their helpful comments on an earlier draft. We thank the Bushfire Front Inc. for contributing funds to assist with the fieldwork.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

The work was supported by the Bushfire Front Inc. [na].

ORCID

A. Wills http://orcid.org/0000-0002-4349-5053
V. Densmore http://orcid.org/0000-0003-0121-8709

References

Alexander ME. 1982. Calculating and interpreting forest fire intensities. Canadian Journal of Botany. 60(4):349–357. doi:10.1139/b82-048.

Alexander ME. 2000. Fire behaviour as a factor in forest and rural fire suppression. Wellington: Forest Research, Rotorua, in association with the National Rural Fire Authority. Forest Research Bulletin No. 197, Forest and Rural Fire Scientific and Technical Series, Report No. 5.

Alexander ME, Cruz MG. 2019. Fireline intensity. In: Manzello S, editor. Encyclopedia of wildfires and Wildland-Urban Interface (WUI) fires. p. 453–460. doi:10.1007/978-3-319-51727-8_52-12.

Anderson HE. 1970. Forest fuel ignitability. Fire Technology. 6(4):312–319. doi:10.1007/BF02588932.

Arroyo LA, Pascual C, Manzanera JA. 2008. Fire models and methods to map fuel types. Forest Ecology and Management. 256(6):1239–1252. doi:10.1016/j.foreco.2008.06.048.

Ashton DH, Attiwill PM. 1994. Tall open forests. In: Groves R, editor. Australian vegetation. 2nd ed. Cambridge (UK): Cambridge University Press; p. 157–196.

Birk EM, Simpson RW. 1980. Steady state and the continuous input model of litter accumulation and decomposition in Australian eucalypt forests. Ecology. 61(3):481–485. doi:10.2307/1937411.

Bradshaw FJ. 2015. Reference material for karri forest silviculture. Perth (Australia): Western Australian Department of Parks and Wildlife. Technical Report FEM067.

Bradshaw FJ, Rayner ME. 1997. Age structure of the karri forest: 1. Defining and mapping structural development stages. Australian Forestry. 60(3):178–187. doi:10.1080/00049158.1997.10676140.

Bradstock RA, Hammill KA, Collins L, Price O. 2010. Effects of weather, fuel and terrain on fire severity in topographically diverse landscapes of south-eastern Australia. Landscape Ecology. 25(4):607–619. doi:10.1007/s10980-009-9443-8.

Burrows ND. 1994. Experimental development of a fire management model for jarrah (*Eucalyptus marginata*) Forest [PhD thesis]. Canberra (Australia): Department of Forestry, Australian National University.

Burrows ND. 1999a. Fire behaviour in jarrah forest fuels: 1. Laboratory experiments. CALMScience. 3:31–56.

Burrows ND. 1999b. Fire behaviour in jarrah forest fuels: 2. Field experiments. CALMScience. 3:57–84.

Burrows ND. 2001. Flame residence time and rates of weight loss of eucalypt forest fuel particles. International Journal of Wildland Fire. 10(2):137–143. doi:10.1071/WF01005.

Burrows N, McCaw L. 2013. Prescribed burning in southwestern Australian forests. Frontiers in Ecology and the Environment. 11(s1): e25–34. doi:10.1890/120356.

Burrows N, Wardell-Johnson G. 2003. Interactions of fire and plants in south-western Australia's forested ecosystems: a review. In: Burrows N, Abbott I, editors. Fire in South-Western Australian ecosystems: impacts and management. Leiden (Netherlands): Backhuys; p. 225–268.

Byram GM. 1959. Combustion of forest fuels. In: Davis K, editor. Forest fire: control and use. New York: McGraw-Hill; p. 61–89.

Cawson JG, Hemming V, Ackland A, Anderson W, Bowman D, Bradstock R, Brown TP, Burton J, Cary GJ, Duff TJ, et al. 2020. Exploring the key drivers of forest flammability in wet eucalypt forests using expert-derived conceptual models. Landscape Ecology. 35 (8):1775–1798. doi:10.1007/s10980-020-01055-z.

Cheney NP. 1990. Quantifying bushfires. Mathematical and Computer Modelling. 13(12):9–15. doi:10.1016/0895-7177(90)90094-4.

Cheney NP, Gould JS, McCaw WL, Anderson WR. 2012. Predicting fire behaviour in dry eucalypt forest in southern Australia. Forest Ecology and Management. 280:120–131. doi:10.1016/j.foreco.2012.06.012.

Christensen PES, Abbott I. 1989. Impact of fire in the eucalypt forest ecosystem of southern Western Australia: a critical review. Australian Forestry. 52(2):103–121. doi:10.1080/00049158.1989.10674542.

Collins L, Hunter A, McColl-Gausden S, Penman TD, Zylstra P. 2021. The effect of antecedent fire severity on reburn severity and fuel structure in a resprouting eucalypt forest in Victoria, Australia. Forests. 12 (4):450. doi:10.3390/f12040450.

Cruz MG, Alexander ME, Fernandes PM. 2022. Evidence of a lack of fuel effect on forest and shrubland rates of spread under elevated fire danger rating conditions: implications for modelling and management. International Journal of Wildland Fire. 31(5):471–479. doi:10.1071/WF21171.

Cruz MG, Cheney NP, Gould JS, McCaw WL, Kilinc M, Sullivan AL. 2021. An empirical-based model for predicting the forward rate of spread of wildfires in eucalypt forests. International Journal of Wildland Fire. 31 (1):81–95. doi:10.1071/WF21068.

Cruz MG, Gould JS, Hollis JJ, McCaw WL. 2018. A hierarchical classification of wildland fire fuels for Australian vegetation types. Fire. 1(1):13. doi:10.3390/fire1010013.

Cruz MG, Sullivan A. 2016 Nov 4. Comment on the forest flammability model (FFM) of Zylstra et al. (2011) and the contents of Zylstra (2016). Canberra (Australia): Memo Commonwealth Scientific and Industrial Research Organisation Division of Land and Water.

Cruz MG, Sullivan AL, Gould JS, Hurley RT, Plucinski MP. 2018. Got to burn to learn: the effect of fuel load on grassland fire behaviour and its management implications. International Journal of Wildland Fire. 27 (11):727. doi:10.7//WFI18082.

DENR. 2012. Overall fuel hazard guide for south Australia. 2nd ed. Adelaide (Australia): Department of Environment and Natural Resources.

Dickinson KJM, Kirkpatrick JB. 1985. The flammability and energy content of some important plant species and fuel components in the forests of Southeastern Tasmania. Journal of Biogeography. 12(2):121–134. doi:10.2307/2844836.

Dimitrakopoulos AP, Papaioannou KK. 2001. Flammability assessment of Mediterranean forest fuels. Fire Technology. 37(2):143–152. doi:10.1023/A:1011641601076.

Duff TJ, Keane RE, Penman TD, Tolhurst KG. 2017. Revisiting wildland fire fuel quantification methods: the challenge of understanding a dynamic, biotic entity. Forests. 8(9):351. doi:10.3390/f8090351.

Etchells H, O'Donnell AJ, McCaw WL, Grierson PF. 2020. Fire severity impacts on tree mortality and post-fire recruitment in tall eucalypt forests of southwest Australia. Forest Ecology and Management. 459:117850. doi:10.1016/j.foreco.2019.117850.

Fernandes PM. 2015. Empirical support for the use of prescribed burning as a fuel treatment. Current Forestry Reports. 1(2):118–127. doi:10.1007/s40725-015-0010-z.

Fernandes PM, Botelho HS. 2003. A review of prescribed burning effectiveness in fire hazard reduction. International Journal of Wildland Fire. 12(2):117–128. doi:10.1071/WF02042.

Fernandes PM, Cruz MG. 2012. Plant flammability experiments offer limited insight into vegetation–fire dynamics interactions. The New Phytologist. 194(3):606–609.

Filkov AI, Tuan N, Mathews S, Telfer S, Penman TD. 2020. Impact of Australia's catastrophic 2019/20 bushfire season on communities and environment. Retrospective analysis and current trends. Journal of Safety Science and Resilience. 1:44–56. doi:10.1016/j.jnlssr.2020.06.009.

Gill AM, Zylstra P. 2005. Flammability of Australian forests. Australian Forestry. 68(2):87–93. doi:10.1080/00049158.2005.10674951.

Gould J, McCaw W, Cheney P. 2011. Quantifying fine fuel dynamics and structure in dry eucalypt forest (*E. marginata*) in Western Australia for fire management. Forest Ecology and Management. 262(3):531–546. doi:10.1016/j.foreco.2011.04.022.

Gould JS, Cruz M. 2012. Australian fuel classification: stage II. Ecosystem sciences and climate adaption flagship. Canberra (Australia): Commonwealth Scientific and Industrial Research Organisation.

Gould JS, McCaw WL, Cheney NP, Ellis PF, Knight IK, Sullivan AL. 2007. Project Vesta, fire in dry eucalypt forest: fuel structure, fuel dynamics and fire behaviour. Perth (Australia): Commonwealth Scientific and Industrial Research Organisation and Department of Environment and Conservation. doi:10.1071/9780643101296.

Gould JS, McCaw WL, Cheney NP, Ellis PF, Matthews S. 2007. Field guide: fuel assessment and fire behaviour prediction in dry eucalypt forest. interim ed. Melbourne (Australia): CSIRO Publishing.

Hallam SJ. 1975. Fire and hearth: a study of Aboriginal usage and European usurpation in south-western Australia. Canberra (Australia): Australian Institute of Aboriginal Studies.

Harmon ME, Chad E, Hanson T, DellaSala DA. 2022. Combustion of aboveground wood from live trees in megafires, CA, USA. Forests. 13(3):391. doi:10.3390/f13030391.

Hines F, Tolhurst KG, Wilson AAG, McCarthy GJ. 2010. Overall fuel hazard assessment guide. 4th ed. Melbourne (Australia): Victoria Department of Sustainability.

Hislop S, Stone C, Haywood A, Skidmore A. 2020. The effectiveness of fuel reduction burning for wildfire mitigation in sclerophyll forests. Australian Forestry. 83(4):255–264. doi:10.1080/00049158.2020.1835032.

Hollis JJ, Anderson WR, McCaw WL, Cruz MG, Burrows ND, Ward B, Tolhurst KG, Gould JS. 2011. The effect of fireline intensity on woody fuel consumption in southern Australian eucalypt forest fires.

Australian Forestry. 74(2):81–96. doi:10.1080/00049158.2011.10676350.

Hollis JJ, Gould JS, Cruz MG, McCaw WL. 2015. Framework for an Australian fuel classification to support bushfire management. Australian Forestry. 78(1):1–17. doi:10.1080/00049158.2014.999186.

Jenkins ME, Bedward M, Price O, Bradstock RA. 2020. Modelling bushfire fuel hazard using biophysical parameters. Forests. 11(9):925. doi:10.3390/f11090925.

Jurskis V. 2005. Decline of eucalypt forests as a consequence of unnatural fire regimes. Australian Forestry. 68(4):257–262. doi:10.1080/00049158.2005.10674974.

Keane RE. 2008. Biophysical controls on surface fuel litterfall and decomposition in the northern Rocky Mountains, USA. Canadian Journal of Forest Research. 38(6):1431–1445. doi:10.1139/X08-003.

Luke RH, McArthur AG. 1978. Bushfires in Australia. Canberra (Australia): Australian Government Publishing Service.

Marshal PL, Davis G, Taylor SW. 2003. Using line intercept sampling for coarse woody debris: practitioner's questions addressed. Extension note EN-012, coast forest region, BC Ministry of Forests. British Columbia (Canada): BC Ministry of Forests.

McArdle BH, Anderson MJ. 2001. Fitting multivariate models to community data: a comment on distance-based redundancy analysis. Ecology. 82(1):290–297. doi:10.1890/0012-9658(2001)082[0290:FMMTCD]2.0.CO;2.

McArthur AG. 1962. Control burning in eucalypt forests. Canberra (Australia): Commonwealth of Australia, Forestry and Timber Bureau. Commonwealth of Australia, Forestry and Timber Bureau Leaflet 80.

McArthur AG. 1967. Fire behaviour in eucalypt forests. Canberra (Australia): Commonwealth of Australia, Forestry and Timber Bureau. Commonwealth of Australia, Forestry and Timber Bureau Leaflet 107.

McArthur AG. 1973. Forest fire danger meter mark V. Canberra (Australia): Commonwealth of Australia Forestry and Timber Bureau.

McCarthy GJ, Tolhurst KG, Chatto K. 1999. Overall fuel hazard guide. Melbourne (Australia): Natural Resources and Environment, Victoria. Research Report No. 47.

McCaw LW, Gould JS, Cheney NP, Ellis RMF, Anderson WR. 2012. Changes in behaviour of fire in dry eucalypt forest as fuel increases with age. Forestry Ecology and Management. 271:170–181. doi:10.1016/j.foreco.2012.02.003.

McCaw WL. 2013. Managing forest fuels using prescribed fire – a perspective from southern Australia. Forest Ecology and Management. 294:217–224. doi:10.1016/j.foreco.2012.09.012.

McCaw WL, Neal J, Smith R. 2002. Stand characteristics and fuel accumulation in a sequence of even-aged karri (*Eucalyptus diversicolor*) stands in south-west Western Australia. Forest Ecology and Management. 158(1–3):263–271. doi:10.1016/S0378-1127(00)00719-2.

McCaw WL, Neal JE, Smith RH. 1996. Fuel accumulation following prescribed burning in young even-aged stands of karri (*Eucalyptus diversicolor*). Australian Forestry. 59(4):171–177. doi:10.1080/00049158.1996.10674686.

Morgan GW, Tolhurst KG, Poynter MW, Cooper N, McGuffog T, Ryan R, Wouters MA, Stephens N, Black P, Sheehan D, et al. 2020. Prescribed burning in south-eastern Australia: history and future directions. Australian Forestry. 83(1):4–28. doi:10.1080/00049158.2020.1739883.

Mutch RW. 1970. Wildland fires and ecosystems – a hypothesis. Ecology. 51(6):1046–1051. doi:10.2307/1933631.

Neumann M, Turner J, Lewis T, McCaw L, Cook G, Adams MA. 2021. Dynamics of necromass in Australian ecosystems. Ecosphere. 12(8):e03693. doi:10.1002/ecs2.3693.

O'Connell AM. 1987. Litter dynamics in karri (*Eucalyptus diversicolor*) forests of south-western Australia. The Journal of Ecology. 75(3):781–796. doi:10.2307/2260206.

O'Connell AM. 1989. Nutrient accumulation in and release from the litter layer of karri (*Eucalyptus diversicolor*) forests of southwestern Australia. Forest Ecology and Management. 26(2):95–111. doi:10.1016/0378-1127(89)90038-8.

Olson JS. 1963. Energy storage and the balance of producers and decomposers in ecological systems. Ecology. 44(2):322–331. doi:10.2307/1932179.

Ormeno E, Cespedes B, Sanchez IA, Velasco-García A, Moreno JM, Fernandez C, Baldy V. 2009. The relationship between terpenes and flammability of leaf litter. Forest Ecology and Management. 257(2):471–482. doi:10.1016/j.foreco.2008.09.019.

Peet GB. 1965. A fire danger rating and controlled burning guide for northern jarrah forest of Western Australia. Perth (Australia): Forests Department Western Australia. Forests Department Western Australia Bulletin No. 74.

Peet GB. 1971. Litter accumulation in jarrah and karri forests. Australian Forestry. 35(4):258–262. doi:10.1080/00049158.1971.10675559.

Peet GB. 1972. Fire studies in jarrah (*Eucalyptus marginata* Sm.) forest [master's thesis]. Melbourne (Australia): University of Melbourne.

Plucinski MP. 2019. Contain and control: wildfire suppression effectiveness at incidents and across landscapes. Current Forestry Reports. 5(1):20–40. doi:10.1007/s40725-019-00085-4.

R Core Team. 2020. R: a language and environment for statistical computing. Vienna (Austria): R Foundation for Statistical Computing. https://www.R-project.org/.

Raison RJ, Woods PV, Khanna PK. 1983. Fuel dynamics in recurrently burnt eucalypt forests. Australian Forestry. 46(4):294–302. doi:10.1080/00049158.1983.10674414.

Rossa CG, Fernandes PM. 2017. On the effect of live fuel moisture content on fire rate of spread. Forest Systems. 26(3):eSC08. doi:10.5424/fs/2017263–12019.

Saura-Mas S, Paula S, Pausas JG, Lloret F. 2010. Fuel loading and flammability in the Mediterranean Basin woody species with different post-fire regenerative strategies. International Journal of Wildland Fire. 19(6):783–794. doi:10.1071/WF09066.

Scarff FR, Westoby M. 2006. Leaf litter flammability in some semi-arid Australian woodlands. Functional Ecology. 20(5):745–752. doi:10.1111/j.1365-2435.2006.01174.x.

Silva FR, O'Connor CD, Thompson MD, Martinez JRM, Calkin DE. 2020. Modelling suppression difficulty; current and future applications. International Journal of Wildland Fire. 29(8):29. doi:10.1071/WF19042.

Sneeuwjagt RJ, Kline TS, Stephens SL. 2013. Opportunities for improved fire use and management in California: lessons from Western Australia. Fire Ecology. 9(2):14–25. doi:10.4996/fireecology.0902014.

Sneeuwjagt RJ, Peet GB. 1985. Forest fire behaviour tables for Western Australia. Perth (Australia): Department of Conservation and Land Management.

Stephenson C, Handmer J, Betts R. 2013. Estimating the economic, social and environmental impacts of wildfires in Australia. Environmental Hazards. 12(2):93–111. doi:10.1080/17477891.2012.703490.

Sullivan AI, McCaw WL, Cruz MG, Mathews S, Ellis PF. 2012. Fuel, fire weather and fire behaviour in Australian ecosystems. In: Bradstock R, Gill A, and Williams R, editors. Flammable Australia; fire regimes, biodiversity and ecosystems in a changing world. Melbourne (Australia): CSIRO Publishing; p. 51–78.

Tangren CD. 1976. The trouble with fire intensity. Fire Technology. 12(4):261–265. doi:10.1007/BF02624803.

Thomas PB, Watson PA, Bradstock RA, Penman TD, Price OF. 2014. Modelling surface fine fuel dynamics across climate gradients in eucalypt forests of south-eastern Australia. Ecography. 37(9):827–837. doi:10.1111/ecog.00445.

Thompson MP, Liu Z, Wei Y, Caggiano MD. 2018. Analyzing wildfire suppression difficulty in relation to protection demand. Environmental Risks. 10:45–64.

Tolhurst KG, McCarthy G. 2016. Effect of prescribed burning on wildfire severity: a landscape-scale case study from the 2003 fires in Victoria. Australian Forestry. 79(1):1–14. doi:10.1080/00049158.2015.1127197.

Tumino BJ, Duff TJ, Goodger JQD, Cawson JG, Lázaro A. 2019. Plant traits linked to field-scale flammability metrics in prescribed burns in Eucalyptus forest. PloS One. 14(8):e0221403. doi:10.1371/journal.pone.0221403.

Turner J, Lambert M, Jurskis V, Bi H. 2008. Long term accumulation of nitrogen in soils of dry mixed eucalypt forest in the absence of fire. Forest Ecology and Management. 265(5):1133–1142. doi:10.1016/j.foreco.2008.06.021.

Underwood RJ. 1978. Natural fire periodicity in the karri (*Eucalyptus diversicolor* F. Muell.*) forest*. Perth (Australia): Forests Department of Western Australia. Forests Department of Western Australia Research Paper 41.

Underwood RJ, Sneeuwjagt RJ, Styles HG. 1985. The contribution of prescribed burning to forest fire control in Western Australia: case studies. WAIT Environmental Studies Group Report. 14:153–170.

Van Wagner CE. 1968. The line intercept method in forest fuel sampling. Forest Science. 14:20–26.

Varner JM, Kane JM, Kreye JK, Engber E. 2015. The flammability of forest and woodland litter: a synthesis. Current Forestry Reports. 1(2):91–99. doi:10.1007/s40725-015-0012-x.

Ward D. 1991. Triangular tesselation: a new approach to forest inventory. Forest Ecology and Management. 44(2–4):285–290. doi:10.1016/0378-1127(91)90014-M.

Watson PJ, Penman SH, Bradstock RA. 2012. A comparison of bushfire fuel hazard assessors and assessment methods in dry sclerophyll forest near Sydney, Australia. International Journal of Wildland Fire. 21 (6):755–763. doi:10.1071/WF11034.

Wotton BM, Flannigan MD, Marshall GA. 2017. Potential climate change impacts on fire intensity and key wildfire suppression thresholds in Canada. Environmental Research Letters. 12(9):095003. doi:10.1088/1748-9326/aa7e6e.

Wotton BM, Gould JS, McCaw WL, Cheney NP, Taylor SW. 2011. Flame temperature and residence time of fires in dry eucalypt forest. International Journal of Wildland Fire. 21(3):270–281. doi:10.1071/WF10127.

Zylstra P. 2017. Forests, not fuels. NPA ACT symposium 2017: bushfire management – balancing the risks. Canberra (Australia): National Parks Association.

Zylstra P, Bradstock RA, Bedward M, Penman TD, Doherty MD, Weber RO, Gill AM, Carey GJ. 2016. Biophysical mechanistic modelling quantifies the effects of plant traits on fire severity: species, not surface fuel loads, determine flame dimensions in eucalypt forests. PloS One. 11 (8):e0160715.

Zylstra PJ. 2018. Flammability dynamics in the Australian Alps. Austral Ecology. 43(5):578–591. doi:10.1111/aec.12594.